VOLUME XXIX NUMBER 2

THE

JOURNAL OF GEOLOGY

FEBRUARY-MARCH 1921

VOLCANIC EARTHQUAKES

CHARLES DAVISON
Birmingham, England

Volcanic earthquakes, according to the late Professor Mercalli, are those which have their centers of maximum intensity under or close to the cones of active or semi-extinct volcanoes.[1] Professor Omori somewhat enlarges this definition. "A volcanic earthquake," he says, "may be defined as a seismic disturbance, which is due to the direct action of the volcanic force, or one whose origin lies under, or in the immediate vicinity of, a volcano, whether active, dormant or extinct."[2] Of the two definitions, the latter is the wider in its scope, for it includes the earthquakes which visit extinct volcanoes, such as the Alban Hills near Rome—earthquakes which differ in no important particular from those of an active volcano like Etna or of a dormant volcano such as M. Epomeo in the island of Ischia.

Mercalli follows up his definition of volcanic earthquakes by describing their important properties. The earthquakes, he says, (1) are felt many times in an area which is very restricted, although the shocks are violent; (2) they precede slightly, but sometimes accompany or follow, the eruptions of the neighboring volcano; and (3) they are repeatedly felt in the same area with similar characters

[1] G. Mercalli, *Vulcani e Fenomeni Vulcanici in Italia* (1883), p. 355.

[2] F. Omori, *Bull. Imp. Earthquake Inv. Com.*, Vol. VI (1912), p. 8.

so long as the volcano maintains its activity without notable change. Tectonic earthquakes differ in the following respects from volcanic earthquakes: (1) for the same intensity at the epicenter, they are felt over a much wider area; (2) though they sometimes occur in the immediate neighborhood of active volcanoes, they are as a rule quite independent of volcanic eruptions; and (3) great tectonic earthquakes seldom revisit the same district except at wide intervals of time. It will be seen later that these are not the only important differences between volcanic and tectonic earthquakes. For the present, however, it may be inferred that volcanic earthquakes as a rule originate in shallow foci which are confined to a limited region, while tectonic earthquakes spread from deeply seated foci that are subject to continual change.

Professor Omori notices that, under his definition, tectonic earthquakes may occasionally be included—earthquakes which disturb large areas[1] and are recorded by seismographs at very distant stations. For instance, about thirty hours before the eruption of the Usu-san (north Japan) on July 25, 1910, an earthquake occurred that was felt to a distance of 87 miles from the volcano and was recorded at a distance of 475 miles.[2] The beginning of the great eruption of the Sakura-jima (south Japan) on January 12, 1914, was followed after a few hours by an earthquake that damaged houses in Kagoshima and the surrounding country and was recorded in European observatories and probably in all parts of the world. Moreover, one month later, on February 13, another strong earthquake took place during an eruption of the Iwo-jima, a volcano belonging to the same chain as the Sakura-jima.[3] To these examples may be added the destructive Hawaiian earthquake of April 2, 1868, which originated in or near the southern part of Hawaii at nearly the same time as great eruptions of

[1] The occurrence of such earthquakes has long been recognized. For instance, G. P. Scrope, in his *Considerations on Volcanos* (1825), states that "those shocks . . . . which are felt to a considerable distance, are probably caused by new rents produced in the solid subjacent strata supporting or surrounding the mountain, and enter into that class of earthquakes which were discussed in a former chapter," that is, of tectonic earthquakes (p. 155).

[2] F. Omori, *Bull. Imp. Earthquake Inv. Com.*, Vol. V (1911), p. 15; Vol. VI (1912), p. 9.

[3] *Ibid.*, Vol. VIII (1914), p. 23; see also *Nature*, Vol. XCII (1914), pp. 716–17.

Kilauea and Mauna Loa, and was certainly felt in the island of Kauai, about 350 miles from the epicenter, or probably over an area of 375,000 square miles.[1]

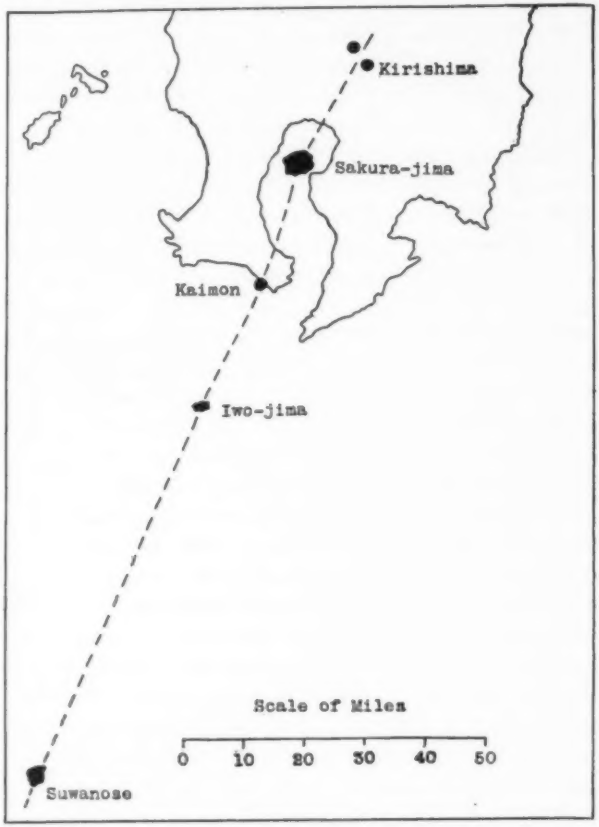


FIG. 1.—Map of volcanic chain in south Japan

It is of some consequence to decide whether such earthquakes should be regarded, as they would be under Professor Omori's definition, as volcanic earthquakes. The course of the volcanic

[1] See an admirable paper by H. O. Wood, "On the Earthquakes of 1868 in Hawaii," *Bull. Seis. Soc. of America*, Vol. IV (1914), pp. 169-203.

chain of southern Japan referred to in the last paragraph is shown in the accompanying sketch map (Fig. 1), and it is interesting to notice the progressive awakening from north to south of the volcanic foci along its course. On November 18, 1913, the Kirishima-yama broke out in strong eruption, which lasted into the following year. The Sakura-jima followed on January 12, 1914; and, about a month later, the Iwo-jima. When three volcanoes, situated as these are and all of infrequent activity, break into eruption so nearly together, and when two of the eruptions are accompanied by strong and deeply seated earthquakes, it would seem natural to ascribe both phenomena to a common cause—the earthquakes directly, and the eruptions indirectly—to the stress accumulation along the whole volcanic chain.[1]

It seems to me, then, that tectonic earthquakes which originate in the immediate neighborhood of volcanoes and even concurrently with eruptions of the same, are not directly of volcanic origin, and should not, by reason of such proximity, be regarded as volcanic earthquakes. I venture, therefore, to suggest that the definitions of such earthquakes given by the two distinguished seismologists referred to should be somewhat modified and should be replaced by the following: A volcanic earthquake is an earthquake directly due to the operations which result or tend to result in a volcanic eruption or is due to relative movements, by whatever cause they may be produced, along fractures of the volcanic mass, whether the volcano itself is active, dormant, or extinct.

Adopting this as the definition of a volcanic earthquake, I propose in the first section of this paper to describe the earthquakes connected with a few typical volcanoes, namely, certain Japanese volcanoes (the Usu-san, the Asama-yama, and the Sakura-jima) and Etna, as examples of active volcanoes, and M. Epomeo in Ischia and the Alban Hills near Rome as examples of dormant and extinct volcanoes respectively. In the second section is given a summary of the characteristic phenomena of volcanic earthquakes; and in the third and last section the modes of origin of volcanic earthquakes will be considered.

[1] F. Omori, *Bull. Imp. Earthquake Inv. Com.*, Vol. VII (1914), pp. 23–24.

I. DESCRIPTION OF SOME VOLCANIC EARTHQUAKES

1. JAPANESE VOLCANOES

Usu-san and Sakura-jima.—The Usu-san is situated near the southwest end of Hokkaido, the northern island of Japan, and the Sakura-jima in the Bay of Kagoshima on the south coast of Kyushu, the southern island. The last eruption of the Usu-san began at 10 P.M. on July 25, 1910, and that of the Sakura-jima at 10 A.M. on January 12, 1914.

Both eruptions were preceded by a large number of earthquakes. Those of the Usu-san outburst began on July 21. At Nishi-Monbets, about 5 miles from the center of the volcano, 25 shocks were felt on July 22, 110 on July 23, 351 on July 24, and 165 on July 25. Once the eruption had begun, the seismic frequency decreased. At Sapporo, about 44 miles from the volcano, the earthquakes were registered by a horizontal pendulum seismograph, the numbers being 1 (at 4:18 P.M.) on July 21, 3 on July 22, 23 on July 23, 76 on July 24, 84 on July 25; after the eruption there was a rapid decline in frequency, the numbers being 26 on July 26, 15 on July 27, 5 on July 28, 6 on July 29, and 1 on July 30. The eruption continued until the end of the year.[1]

At Kagoshima, which is about 6 miles from the center of the Sakura-jima, the first earthquake was felt at 3:41 A.M. on January 11, 1914. At the Kagoshima Observatory the earthquakes were recorded by a Gray-Milne seismograph, the average hourly frequency being 4.1 from 3 to 11 A.M. on January 11, 12.4 from 11 A.M. to 8 P.M., and 19.5 from 8 P.M. on January 11 to 10 A.M. on January 12. The greatest hourly numbers were 28 at 8–9 P.M. on January 11 and 27 at 3–4 A.M. on January 12. The total number of shocks registered from 3 A.M. on January 11 to 10 A.M. on January 12 was 418. After the first eruption at the last-mentioned hour, there was a marked decline in earthquake frequency, the numbers being: 10–11 A.M., 17; 11–noon, 11; noon–1 P.M., 6; 1–2 P.M., 3; 2–3 P.M., 5; 3–4 P.M., 2; 4–5 P.M., 2; 5–6 P.M., 2. At 6:30 P.M., the seismograph was injured by the strong tectonic earthquake referred to above.[2]

[1] *Ibid.*, Vol. V (1911), pp. 8–17.

[2] *Ibid.*, Vol. VIII (1914), pp. 9–14, 22–27.

Thus, both eruptions were preceded by a marked increase in seismic frequency, followed by a marked decrease, the maxima occurring 24 hours before the first outburst of the Usu-san and about 13 and 6 hours before that of the Sakura-jima.[1]

Observations were made with a portable horizontal tromometer erected by Professor Omori at Nishi-Monbets (5 miles from the Usu-san) from July 30 to August 6, and at the West-Kohan School (Sobets) at the foot of the East Maru-yama from August 6 to 10. At this place, which is close to the nearest craterlet, series of well-defined, small, quick, unfelt vibrations, called micro-tremors by Professor Omori, were registered, which were entirely absent from the records at Nishi-Monbets. The mean range of motion was in every case less than one-tenth of a millimeter; but the principal periods of the tremors (.53, 1.08, 1.59, 2.14 seconds) were practically identical with those of earthquake vibrations recorded at Nishi-Monbets (.53, 1.01, 1.58, 2.43 seconds). It would seem, then, that the micro-tremors are in reality true earthquake vibrations, but so weak that they cannot be recorded more than a few miles from the origin. Professor Omori notices that the shortest of the foregoing periods is approximately one-half, one-third, and one-quarter of the other periods. He also shows that moderate explosions from even the nearest craterlet were not as a rule accompanied by marked micro-tremors; whereas violent explosions from that and other craterlets were usually accompanied, and often preceded by several minutes, by well-pronounced micro-tremors. The tremors, however, were not confined to the epochs of explosions. They sometimes occurred when the smoke ejections from the different craterlets were insignificant and even when they had completely ceased. At such times, as Professor Omori suggests, eruptions were perhaps prevented by the temporary stoppage of the craterlets.[2]

Asama-yama.—The Asama-yama, one of the greatest of Japanese volcanoes, rises from the plateau of the central island of

[1] Professor Omori's observations give precision to a fact which has long been known. "It is," says G. P. Scrope in his *Considerations on Volcanos* (1825), "a remark common to the observations made on almost all volcanic eruptions, that local earthquakes always precede the emission of lava currents, and cease while the lava is flowing, to recommence when it has stopped" (p. 155).

[2] *Op. cit.*, Vol. V (1911), pp. 31–38.

Japan to a height of 8,140 feet above the sea. After a prolonged period of rest, it has been subject for about six years to a series of strong explosions, the first of which occurred on February 13, 1908.

Observations with horizontal pendulum seismographs were instituted by Professor Omori at two stations on the southwest flank of the volcano, Yuno-taira and Ashino-taira, at heights of 6,306 and 4,422 feet above the sea. Owing to weather conditions, the observations at the former station were confined to the summer months.

The seismograms obtained at these places showed that there were two distinct types of earthquakes, some being independent of any outburst of the volcano, while others were invariably the results of explosions.

The two types of earthquakes are characterized by several marked differences, of which the following are the more important:

a) The shocks without explosions consisted only of minute quick vibrations, while those with explosions consisted of slow movements (of as much as 2.6 and 5.3 seconds' period), on which after a few seconds quick vibrations were superposed.

b) The earthquakes without explosions were distinctly stronger than the others, probably because, as Professor Omori suggests, a great part of the energy of the explosions is expended in the projection of rock fragments and débris. Of 1,485 earthquakes without explosions, 21 per cent were sensible at Yuno-taira; of 8,847 earthquakes with explosions, only 0.3 per cent were sensible. Moreover, the strong earthquake of May 26, 1908, which did not accompany an explosion and which evidently originated in the volcano itself, was felt over an area of 2,400 square miles.[1]

c) The earthquakes without explosions were of shorter duration than those with explosions, the averages for the former being 16.7 seconds in 1911 and 15.0 seconds in 1912, and for the latter 33.2 seconds in 1911 and 32.7 seconds in 1912.

d) The two types of earthquakes alternate in frequency. During the two years, 1911–12, the maxima of the earthquakes

[1] It may be added that the Usu-san explosions of 1910 were preceded by many sensible earthquakes, a few of them strong; but, as a rule, they were unaccompanied by sensible shocks.

without explosions occurred at 3–4 A.M., 8–9 A.M., 1–2 P.M., and 8–9 P.M., while the minima of the earthquakes with explosions occurred at 3–4 A.M., 8–9 A.M., 2–3 P.M., and 9–10 P.M. The minima of the former occurred at 6–7 A.M., 11–12 A.M., 6–7 P.M., and 11–12 P.M., while the maxima of the latter occurred at 5–6 A.M., noon–1 P.M., 4–5 P.M., and 1–2 A.M. In August, 1911, the earthquakes with eruptions attained their maximum frequency (205) for the year, and the earthquakes without eruptions their minimum frequency (38); in October, 1912, there was a maximum of earthquakes with eruptions (626) and a minimum of earthquakes without eruptions (10). A similar relation is shown in the variation of frequency from one year to another, as will be seen in the following table:[1]

	Earthquakes without Eruptions			Earthquakes with Eruptions		
	Sensible	Unfelt	Total	Strong Explosions	Small Outbursts	Total
1911.....	57	321	378	0	577	577
1912.....	124	563	687	0	1111	1111
1913.....	6	28	34	25	7101	7126
1914.....	11	37	48	1	30	31
1915.....	44	65	109	0	0	0
1916.....	64	165	229	0	2	2

2. ETNA

Etna rises from a nearly circular base, measuring 428 square miles, to a height of 10,870 feet. Earthquakes occur on all sides of the mountain, and, for many years past, they have been especially frequent beneath its southeastern flank. In the present section, I propose to describe a few typical earthquakes on this flank, and to refer very briefly to the distribution of the epicenters within the area covered by the volcano.

The earthquakes belong as a rule to one of two classes, according as the greater axes of their meizoseismal areas are directed nearly along or perpendicular to the radii from the central crater. They may therefore be called *radial* and *perimetric* earthquakes, respectively.

[1] After May 5, 1914, there was no strong outburst of the Asama-yama.

As examples of radial earthquakes on the southeastern flank, I have selected three which have been studied in perhaps greater detail than others, namely, the Fondo Macchia earthquake of July 19, 1865, the Fleri earthquake of August 8, 1894, and the Linera earthquake of May 8, 1914. The Fondo Macchia earthquake of October 15, 1911, is given as an example of a perimetric earthquake.

Radial earthquakes.—On January 30, 1865, a great eruption took place on the east-northeast flank of Etna, which lasted nearly twelve weeks. Eighty-eight days after its close, on July 19, Fondo Macchia was completely destroyed by an earthquake, and the neighboring villages of Baglio, Rondinello, Scaronazzi, and S. Venerina were seriously damaged, though not ruined. The meizoseismal area was a narrow band directed W.NW. and E.SE., a little over 4 miles in length and about $\frac{2}{3}$ mile wide. Outside this band, the shock was disastrous within an area 5 miles long and $1\frac{1}{4}$ miles wide, represented by the curve *A* on the sketch map (Fig. 2). The intensity of the shock diminished rapidly toward the north, and more slowly toward the south, but at no place more than 12 miles from the epicenter was the shock felt. The area disturbed cannot therefore have exceeded 113, and was probably less than 100, square miles. A number of after-shocks followed this earthquake, 24 being felt in July (3 of them very strong at

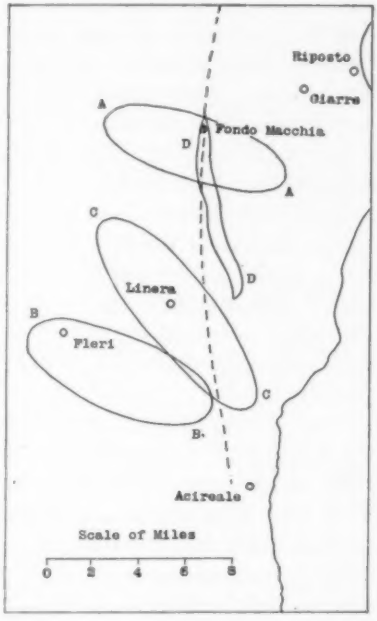


FIG. 2.—Map of earthquakes on southeast flank of Etna.

Fondo Macchia), and several others, more or less slight, in the following month, the series ending on August 23.[1]

The earthquake of August 8, 1894, differed in two respects from many Etnean earthquakes. It occurred while the volcano was in a state of only moderate activity, and it disturbed an area unusually large for the district, although small for a shock of such intensity. It was preceded by a violent shock at 1:58 P.M. on August 7, strongest at Fleri, Zerbate, etc., and felt generally at Catania and Zafferana, and by a few persons at Nicolosi and Trecastagni. Three other shocks followed in the meizoseismal area before the occurrence of the principal shock of the series at 6:16 A.M. on August 8. By this shock, the villages of Fleri, Pisano, Zerbate, etc., were ruined. The meizoseismal area, about 4 miles long from northwest to southeast and 2 miles wide, is represented by the curve *B* in Figure 2. From this area, the intensity of the shock diminished outward rather, but not very, rapidly, the disturbed area including the whole base of Etna and probably on the whole as much as 800 square miles. Within or near the epicentral district, at least 15 after-shocks were felt before the end of the month.[2]

Few, if any, Etnean earthquakes have thrown so much light on the nature and origin of volcanic earthquakes as the remarkable series which culminated in the Linera earthquake of May 8, 1914. They have been studied by Professor G. Platania in one of the most valuable memoirs that we possess on volcanic earthquakes.[3] In all respects except in the shallowness of the foci, they resemble true tectonic earthquakes. They were preceded and followed by long series of accessory shocks, and, along the axis of the meizoseismal area, there were displacements of a pre-existing fault.

Omitting instrumental shocks, the whole series contained 55 earthquakes, 21 being fore-shocks from April 28 to May 7, and 33 after-shocks from May 8 to June 4. Five of the fore-shocks and

[1] A. Riccò, *Boll. Soc. Sism. Ital.*, Vol. XVI (1912), pp. 27–31; M. Baratta, *Boll. Soc. Geogr. Ital.* (1894), pp. 12–13, and *I Terremoti d'Italia*, pp. 442–43.

[2] M. Baratta, *Boll. Soc. Geogr. Ital.* (1894), pp. 6–9, 23.

[3] "Sul periodo sismico del maggio 1914 nella regione orientale dell'Etna," *Pubbl. dell'Ist. di Geogr. Fis. e Vulcan. della R. Univ. di Catania*, No. 5, 1915.

Science & Industry Department

seven of the after-shocks were strong. The broken line on the map (Fig. 3) includes all the places in which houses were damaged by the different shocks of the series. The smaller curves represent the meizoseismal areas of the more important shocks. Thus, the curves 1 and 2 indicate the meizoseismal areas of the double earthquake of May 7 at 6:35 P.M., houses being damaged at Piano d'Api (No. 1) and at Pennisi and Fiandaca (No. 2). At 10 P.M. on the same day, another strong earthquake caused damage at Fossalacqua (No. 3) along a fracture which may be a continuation of that at Fiandaca (No. 2). The principal earthquake occurred at 7:2 P.M. on May 8, and was ruinous within the area bounded by the ellipse (No. 4), the zone of complete ruin being much less wide. With this earthquake also there was a zone of serious damage to houses at Dagala (No. 5), separated from the principal zone by a wide tract of little or no damage to property. Lastly, the curve No. 6 shows the boundary of slight damage near Viagrande wrought by the after-shock of May 26.

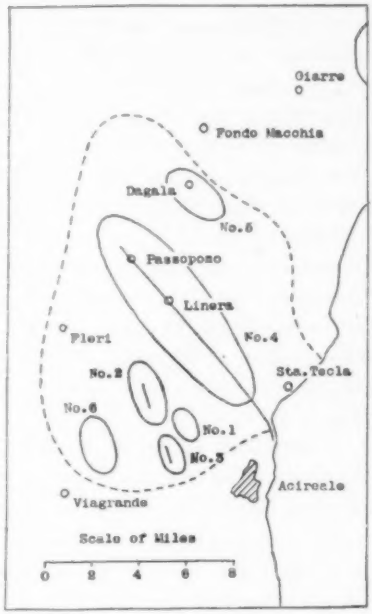


FIG. 3.—Map of Linera earthquakes of 1914

The meizoseismal area of the principal earthquake (bounded by the curve *C* in Fig. 2 and No. 4 in Fig. 3), within which the ruin was practically complete, is very elongated, being about $4\frac{1}{4}$ miles long, with a maximum width near Linera of $1\frac{1}{4}$ miles. In this zone, not only are the houses completely razed to the ground, but the ground itself is crushed. Along the axis of this zone, there runs a slightly sinuous fracture with, in parts, a secondary nearly parallel

fracture separated by a distance of from 2 to 50 or more yards. The most destructive effects of the earthquake are concentrated along this fracture, starting from Passopomo, through Linera, to beyond Mortara. Here the railway line was seriously damaged, the rails being displaced and contorted. The fracture can be followed as far as the seacoast, bending slightly to the south in the neighborhood of Sta. Tecla. Almost throughout the fractured zone there is a change of level, in some places of only an inch or two in others of 15 or 16 inches, and in one, near the seacoast, of more than 3 feet, the ground of the southwest side being left at a higher level than that on the northwest side.[1] The fracture is by no means a recent one, for it has been known since 1879, and Professor Platania states that displacements have occurred along it in previous earthquakes. Nor is it the only fracture along which movements have taken place during this series of earthquakes. There is a second at Fiandaca (No. 2), which was observed during the earthquakes of 1894 and 1907, and which probably corresponds with another at Fossalacqua (No. 3). Near this fracture occurred the greatest damage wrought by the two strong fore-shocks of May 7.

During the interval covered by this series of earthquakes there was a marked increase in the activity of Etna, though the different shocks were not coincident with the volcanic explosions.

Perimetric earthquakes.—On September 10, 1911, a great eruption of Etna began, and, notwithstanding the extraordinary energy of the early phenomena, ceased after only thirteen days of activity. Three weeks later occurred the destructive Fondo Macchia earthquake of October 15, 1911. This earthquake was, however, preceded by at least 10 fore-shocks, the first 5 of which occurred on September 30 at Pisano (intensity 7, Mercalli scale), October 9 (2 shocks) at Piano d'Api (intensity 5), and October 14 at S. Venerina (intensity 6). The principal shock (intensity 10) occurred at 9:52 A.M. on October 15, and was followed by 4 slight after-shocks on October 24 and 1 on November 9.

[1] There is also some evidence of horizontal displacement. A high wall in the upper part of the fractured zone is curved and shifted toward the southeast.

The isoseismal lines of intensities 10, 8, 6, 4, and 2 (Mercalli scale) are shown in Figure 4, the line of intensity 10 being also represented by the curve *D* in Figure 2. The meizoseismal area (bounded by the isoseismal 8) is a slightly sinuous band, running from N.NW. to S.SE., 4 miles long, about $\frac{1}{3}$ mile wide, and $1\frac{1}{4}$ square miles in area. Within it is a band, including Fondo Macchia, in which the destruction of buildings was complete, this band being about 3 miles long and $\frac{1}{4}$ mile wide. Notwithstanding the great intensity within this band, the shock was not felt at places 6 miles to the west, the area within the isoseismal 4 contained not more than about 70 square miles, and the whole district shaken only about 230 square miles. The mean duration of the shock was about 8 seconds.

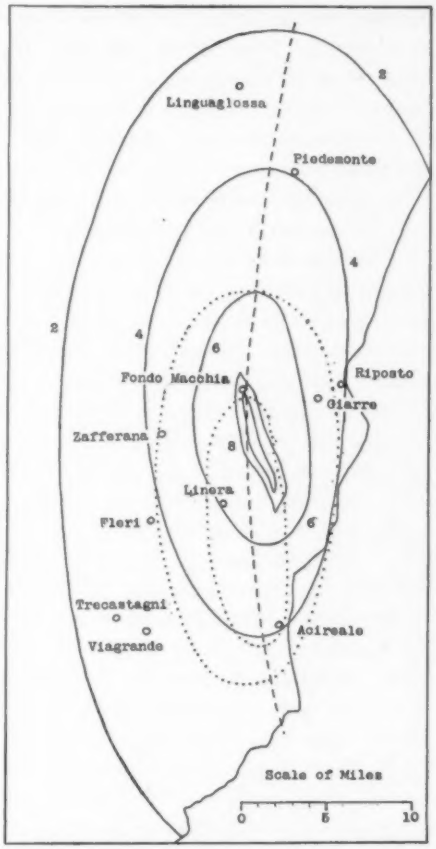


FIG. 4.—Map of Fondo Macchia earthquake of October 15, 1911.

During the eighteen years (1893–1911) preceding this earthquake, 27 shocks more or less strong originated within the elliptical

area represented by the outer dotted line in Figure 4. Six of these earthquakes were of ruinous strength, with their epicenters at Fondo Macchi, Zerbate, S. Leonardello, and Aci Platania, all included within the area represented by the smaller dotted ellipse in Figure 4. The two ellipses have their longer axes coinciding with those of the isoseismal lines of the Fondo Macchia earthquake of 1911. Close to these axes and nearly parallel to them, runs a fault known as the *Timpa della Scala* and represented by the broken line on the map. The western limb at the south end has undergone, and is still undergoing, elevation; while the eastern limb at the north end is subsiding.[1]

Distribution of Etnean earthquakes.—A few of the Etnean earthquakes disturb the whole area of the volcano; but the majority are strongly felt in one or a few of the villages scattered over the mountain sides. In such cases the villages affected cannot be far distant from the epicentral areas, and Dr. M. Baratta, in his great history of Italian earthquakes,[2] has thus found it possible to distinguish the principal seismic zones of this volcanic region. These are twelve in number, the places which give their names to the different zones being shown in Figure 5, in which the dotted line marks out the base of the volcano: (1) Linguaglossa, to the NE.; (2) Randazzo, to the N.; (3) Adernò-Bronte-Maletto, to the W.; (4) Santa Maria di Licodia, to the S.W.; (5) Paternò, to the S.SW.; (6) Belpasso, to the S.; (7) Nicolosi, to the S.; (8) Trecastagni, to the S. SE.; (9) Acireale, to the SE.; (10) Zafferana-Pisano-S. Venerina, to the E.SE.; (11) Macchia Region, to the E.; and (12) Giarre-Riposto, to the E.

Of these zones, the most important at present are those of Santa Maria di Licodia, Nicolosi, Trecastagni, Acireale, Zafferana-Pisano-S. Venerina, and the Macchia Region. The Fleri earthquake of 1894, described above, is included in the Acireale zone, the Linera earthquake of 1914 in the Zafferana zone, and the Fondo Macchia earthquakes of 1865 and 1911 in the Macchia zone. The Nicolosi zone gives rise to many and violent earthquakes, and it is remarkable that some of the greatest are quite

[1] A. Riccò, *Boll. Soc. Sis. Ital.*, Vol. XIX (1912), pp. 9–38.

[2] *I Terremoti d'Italia*, pp. 829–33.

Science & Industry
Department

local. For instance, the earthquake of May 11, 1901, damaged many houses in Nicolosi (intensity 8), and yet was only just perceptible at a distance of 3 or 4 miles.[1] The earthquake of May 14, 1898, is typical of the S. Maria di Licodia zone; nearly all the

FIG. 5.—Map of Etna and seismic districts

houses in S. Maria di Licodia were damaged, and slight injury occurred in other villages on the southwest slope from Belpasso to Adernò, the shock being thus rather more widely felt than the Nicolosi earthquake.[2]

[1] S. Arcidiacono, *Boll. dell' Accad. Gioenia di Sci. Nat. in Catania*, Fasc. 70 (1901).

[2] A. Riccò, *op. cit.*, Fasc. 53–54 (1898).

For many years past the most active zones have been those between the eastern and southern radii. But the seismic foci migrate from one zone to another without (at present) any apparent law. Take, for instance, the earthquakes of one year only, the year 1903.[1] On January 30 there was a shock of intensity 5 at Giarre, Zafferana, Milo, Viagrande, Linguaglossa, and Randazzo (the epicenter being perhaps in zone 12); on March 8, one of intensity 4 between Nicolosi and Mascalucia, but hardly felt at either of these places although they are only 4 miles apart (zone 7); on March 11, one of the same intensity at S. Venerina (zone 10); on March 24, a very slight shock at Belpasso (zone 6); on April 3, a shock of intensity 5, and on April 4 and 5 very slight shocks at S. Venerina (zone 10); on April 7, a shock of intensity 5 at Linguaglossa and Milo (zone 1); on April 13, one of intensity 4 at Biancavilla (zone 4?); on April 19, a slight shock at Paternò (zone 5); on May 26, a very strong shock with slight damage at Trecastagni (zone 8), and only feebly felt at Viagrande, less than a mile away; on June 1, 14 shocks (2 of them of intensity 6) at Pedara and Viagrande; on June 3, 3 shocks at Viagrande; on June 5, 1 shock, and on June 7, 2 shocks, at Trecastagni and Viagrande; on June 11, a slight shock at Trecastagni; and on June 16, 2 very slight shocks at Viagrande (all 23 shocks in zone 8); on July 21, a very slight shock at Belpasso (zone 6); on July 30, a sensible shock at Biancavilla (zone 4?); on August 6, 4 shocks of intensity 4 at Nicolosi, Trecastagni, Zafferana, Milo, and Biancavilla (zone 7?); and, lastly, on November 20, a strong earthquake of intensity 6 at Viagrande, Zafferana, Milo, S. Venerina, Acireale, and Linguaglossa (zone 10). Thus, seven out of the twelve Etnean zones were probably in action in this one year.

3. MONTE EPOMEO (ISCHIA)

The island of Ischia, 6 miles long from east to west and 5 miles in width, is separated from the Italian coast by a distance of only 6 miles. A large part of the island is occupied by the old crater of Monte Epomeo, a volcano which must be regarded as dormant rather than extinct, for the last eruption occurred in

[1] S. Arcidiacono, *Bull. dell' Accad. Gioenia di Sci. Nat. in Catania*, Fasc. 79 (1903).

1302, and the one before that a thousand years earlier. These eruptions, as well as their more recent predecessors, took place from new vents chiefly on its eastern and northeastern flanks. All of them began suddenly, were accompanied by violent earthquakes, and were preceded by long intervals of repose.

Such an interval, one of more than four centuries, followed the last eruption, and during that time there were no earthquakes

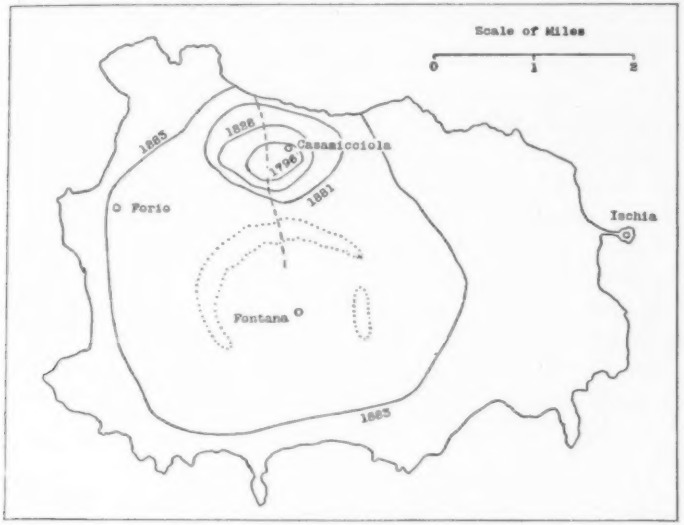


FIG. 6.—Map of Ischian earthquakes

of any consequence in the island. Then, during one night—July 28–29, 1762—as many as 62 earthquakes were felt at Casamicciola, some of them strong enough to damage buildings. On March 18, 1796, a severe earthquake occurred, which caused destruction of buildings in Casamicciola alone; on February 2, 1828, one still stronger, which again wrought destruction in that town; others of less consequence, but still strong, occurred on March 6, 1841, and August 15–16, 1867; the last of all being the destructive earthquakes of March 4, 1881, and July 28, 1883.

In the accompanying map (Fig. 6) the dotted lines represent the boundaries of those portions of the central crater of Epomeo

which are still standing, and the continuous lines the boundaries of the areas within which buildings suffered marked damage by the earthquakes of 1796, 1828, 1881, and 1883. It will be noticed that these areas show a progressive increase in size. The broken line, slightly curved, shows the position of the radial fracture with which the earthquakes were probably connected; and it is important to notice that the chief damage wrought by the earthquakes of 1881 and 1883 was concentrated along this line near Casamicciola.

These earthquakes were studied in great detail by the late Dr. H. J. Johnston-Lavis. The isoseismal bounding the area of complete destruction in 1881 includes only ½ square mile, the area of partial though serious destruction about 2 square miles, and that within which buildings were slightly damaged about 5 square miles. Still farther, the shock continued to diminish rapidly in intensity. It was felt in the neighboring island of Procida, and by some persons, though very slightly, on the Italian coast, the total area being probably less than 300 square miles. From the inclination of the fissures made in buildings, Dr. Johnston-Lavis estimated the mean depth of the focus at about ⅓ mile. The earthquake was followed by a few slight after-shocks on March 7 (2 shocks), 11–12, 15–16, 17–18, and 27(?), April 5 and 6, and July 18.

The earthquake of July 28, 1883, was much stronger, and resulted in great loss of life at Casamicciola. It was preceded at that place by a slight shock on July 24, and by an earth-sound a quarter of an hour beforehand. The areas of complete, partial destruction and slight damage were respectively 3, 11, and 30 square miles. In this earthquake, also, the intensity diminished very rapidly outward. The shock was felt in Italy near the coast and by a few persons in Naples, which is 20 miles from Casamicciola. The disturbed area can hardly therefore have contained more than 1,250 square miles. The mean depth of the focus was again found to be about ⅓ mile. The shock was remarkable for the entire absence of preliminary sound or tremor and for its great initial strength, a great part of the ruin being caused during the first few seconds. Between July 28 and August 3, 21 slight

after-shocks were felt in Casamicciola. This, however, was not the only center in action, for several were recorded at the town of Ischia only.[1]

4. ALBAN HILLS

About 15 miles to the southeast of Rome lies a group of extinct volcanoes containing several circular lakes which evidently occupy old craters of the system. The principal hill, Monte Cavo, of which the other and smaller hills may be regarded as lateral cones, rises to a height of nearly 3,000 feet. There is no certain evidence of activity during historic times.

The earthquakes of this district are less frequent and destructive than those of the much larger Etnean region, but in other respects they resemble them closely, and especially in the constant migration of activity from one part of the volcano to another.

One of the most recent in the district is that of February 21, 1906. It was preceded by six very slight fore-shocks, one on February 20, at Ariccia, the others on February 21, at Albano. The principal shock occurred at 9:49 P.M. on February 21, and, from that time until February 23, there were 6 very slight after-shocks. The isoseismal lines of the principal earthquake, which was of intensity 5–6 (Mercalli scale), are represented approximately in Figure 7. They are rather close together, indicating a rapid decline in the intensity of the shock from the epicenter, though a decline less rapid than in other earthquakes of the same district or of the Etnean region. The mean duration of the shock was nearly 4 seconds.[2]

Dr. M. Baratta defines the following seismic zones among the Alban Hills (Fig. 7): (1) Colonna; (2) Montecompatri; (3) Monte Porzio; (4) Frascati; (5) Rocca di Papa-Monte Cavo; (6) Albano; (7) Ariccia; (8) Nemi; and (9) Velletri.[3] To these districts should perhaps be added: (10) Genzano-Civitalavinia.

[1] G. Mercalli, *L'isola d'Ischia ed il terremoto del 28 luglio 1883* (Milan, 1884); H. J. Johnston-Lavis, *Monograph of the Earthquakes of Ischia* (1885). A summary of these and other memoirs on the Ischian earthquakes is given in my *Study of Recent Earthquakes*, pp. 45–73.

[2] G. Agamennone, *Boll. Soc. Sis. Ital.*, Vol. XXI (1918), pp. 47–101.

[3] *Terremoti d'Italia*, pp. 778–80.

Of these zones, Nos. 1–4 lie on the northern half, and Nos. 6–10 on the southern half, of the volcano.

As in the Etnean region, there is at present no apparent law in the transference of the epicenters from one zone to another. The nature of that transference may be shown by a brief reference to the more important earthquakes of the last forty years. On September 2, 1883, an earthquake of intensity 7 (Mercalli scale)

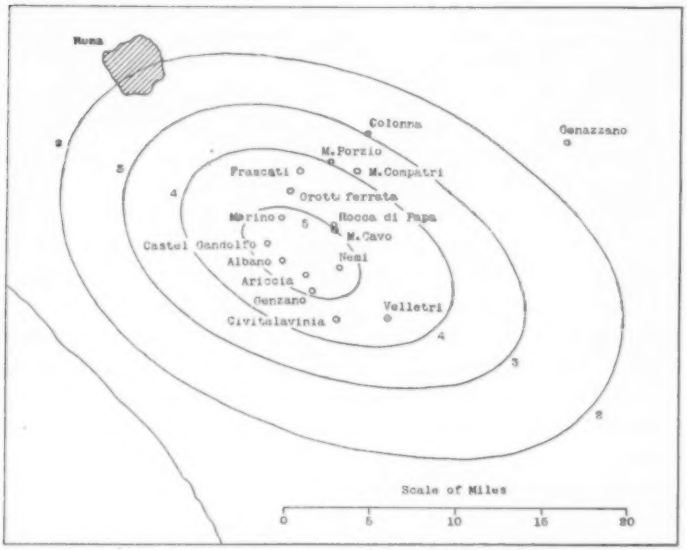


FIG. 7.—Map of Albano earthquake of February 21, 1906

caused slight damage at Frascati, Grottaferrata, Rocca di Papa, and Monte Cavo (zone 4), the axis of the area of maximum intensity being directed southeast or along a radius from the summit of Monte Cavo; on January 17, 1886, there was a very strong shock at Ariccia (zone 7); on January 22, 1892, a shock with its epicenter between Genzano and Civitalavinia (zone 10); on May 8, 1897, a strong shock without damage at Colonna, the axis of the area of maximum intensity being directed southwest or along a radius (zone 1); on November 6, 1897, a shock at Civitalavinia

Scie... Library
Department

(zone 10), followed a week later (on November 13) by one with its epicenter near Velletri (zone 9); on July 19, 1899, the strongest shock of the series (intensity 8), causing some damage at Frascati (zone 4) and rather less at Marino, the mean duration of the shock $3\frac{1}{2}$ seconds, registered at Lubiano (298 miles to the north) and Catania (318 miles to the south); on October 12, 1902, a shock of intensity 6 at Genzano (zone 10); on February 21, 1906, one of intensity 5–6 at Albano (zone 6); and, lastly, on October 6, 1909, a shock at Frascati (zone 4). Thus, of these ten earthquakes, four originated on the north side, and six on the south side, of the volcano; while six of the ten seismic zones were in action.

II. CHARACTERISTICS OF VOLCANIC EARTHQUAKES

a) While volcanic earthquakes often occur in close connection with eruptions—either shortly before, during, or shortly after them—they seldom coincide with an outburst, except in the case of the weak tremors with which the Japanese records have made us familiar. Nor do the almost contemporaneous earthquakes and eruptions always occur in the same part of the volcano. The Fondo Macchia earthquakes of 1865 and 1911 were felt in a district to the east of the central crater of Etna, while they followed closely on eruptions from the northeastern flank. Some earthquakes, again, occur in active volcanic regions without the accompaniment of any change in volcanic activity; others in regions in which the volcanoes have been extinct for many centuries.

b) In volcanic earthquakes the intensity of the shock is often great near the center of an extremely small disturbed area. The relation between the intensity and the area is by no means constant. On the one hand, we may have an earthquake like that of Nicolosi in 1901, destroying houses in a minute epicentral area and yet imperceptible at a distance of more than 4 miles, or one like the Ischian earthquake of 1883, leveling every building within an area of 3 square miles, and yet felt within an area of not more than 1,250 square miles. On the other hand, we may have an earthquake like the Albano earthquake of 1906, not strong enough to damage houses at the epicenter and yet felt over an area of 535 square miles.

c) The sound and tremor, with which tectonic earthquakes usually begin, are either absent from volcanic earthquakes, or else of duration so short as to be almost imperceptible.

d) The duration of the shock in volcanic earthquakes is usually short, being very often less than 5 seconds.

e) The length of the focus is inconsiderable when compared with that of tectonic earthquakes. Even in the strongest of volcanic earthquakes, it rarely exceeds 4 or 5 miles, whereas the average length of the focus in British earthquakes (omitting the weakest) is about 12 or 13 miles. This conclusion is also supported by the brief duration of the shock.

f) Some, but not all, volcanic earthquakes are preceded and followed by a rather large number of accessory shocks. In this they resemble tectonic earthquakes. But the after-shocks of volcanic earthquakes are distinguished by the short period of their action. For instance, the series of after-shocks in the Albano earthquake of 1906 lasted for 3 days, in the Ischian earthquake of 1883, for 7 days, in the Fleri earthquake of 1894, for about 3 weeks, in the Linera earthquake of 1914, for nearly 4 weeks, and in the Fondo Macchia earthquake of 1865, for 5 weeks.

(*g*) The after-shocks of volcanic earthquakes are practically confined to the epicentral area. They point to little, if any, tendency toward any extension of the original focus.

h) In a volcanic system such as that of Etna or the Alban Hills earthquakes occur in many different zones, and seismic activity is subject to frequent and sudden migrations from one zone to another. Nevertheless, in any given zone there is often a certain fixity in the epicenters of successive earthquakes, as in those of Fondo Macchia (Etna) and Casamicciola (Ischia).

The most characteristic of these features is the smallness of the disturbed area considering the intensity of the shock at the epicenter. In Great Britain we have no shocks to be compared in strength with those of Fondo Macchia and Ischia. The strongest of British earthquakes are just capable of causing slight damage to buildings (corresponding to the degree 7 of the Mercalli scale), and the average area disturbed by them is 65,900 square miles. Others of intensity 6, only slightly stronger than the Albano

earthquake of 1906, are felt over an average area of 24,500 square miles.

As will be seen from Figure 8, the rapid decline in the intensity of the shock is due to the shallowness of the focus. The curves marked *A* and *B* in Figure 8 represent the intensities of the shock at different distances from the origin, *A* corresponding to a focus $\frac{1}{4}$ of a mile in depth, *B* to one at a depth of 2 miles. The curves are drawn on the assumptions that the intensity of the shock at any point of the surface varies inversely as the square of the distance from the focus, and that the impulses are such that the intensity of the shocks vertically above both foci is the same.

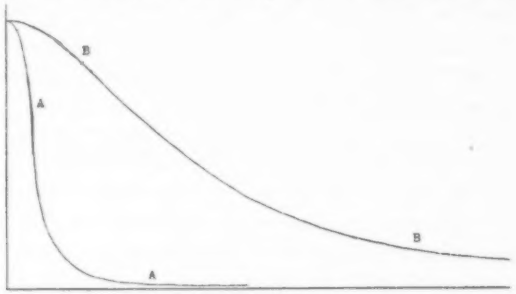


FIG. 8.—Diagram illustrating shallowness of foci in volcanic earthquakes

On these assumptions it follows that the shock that would just be perceptible at a distance of 2 miles from the center for the shallow focus would be perceptible at a distance of 32 miles for the deeper one—that is, the disturbed area of the shock with the deeper focus would be 256 times the disturbed area of the other shock.

It follows, then, that the foci of most volcanic earthquakes are situated at a very slight depth below the surface, and further that the foci vary in depth, the focus of an earthquake like the Nicolosi earthquake of 1901 or the Fondo Macchia earthquake of 1911 being much nearer the surface than that of the Albano earthquake of 1906.

This inference, as to the shallowness of the foci in volcanic earthquakes, is supported by two other lines of evidence. In the

Ischian earthquakes of 1881 and 1883 the depth was estimated, from the inclination of the fissures in walls, to be $\frac{1}{3}$ mile. Again, the duration of the preliminary tremor of an earthquake increases with the distance from the focus, and the practical absence of any such tremor therefore points to the nearness of the focus to the surface.

We may thus conclude: (*a*) that the foci of volcanic earthquakes are situated at a very slight depth below the surface; (*b*) that the foci are usually small and seldom more than 4 or 5 miles in length; (*c*) that the after-shocks, when they occur, originate chiefly within the focus of the principal earthquake; and (*d*), from the discussion of the Etnean and Alban earthquakes, that, while the majority of volcanic earthquakes originate along radial fractures of the mountain, some, and by no means the least important, originate along perimetric fractures.

III. THE ORIGIN OF VOLCANIC EARTHQUAKES

The earthquakes which occur in the neighborhood of active or dormant volcanoes are naturally attributed to the processes which sooner or later tend to result in an eruption. As any sudden displacement of material within the earth's crust may give rise to an earthquake, the processes which have been suggested as possible causes may be grouped under the following heads:

a) The formation of new fractures, or the reopening or extension of old fractures, in the mountain mass, due to the pressure of the column of lava or of gaseous materials in their progress toward the surface.

b) Explosions of any kind, such as those from the sudden generation of steam within the volcano by the access of water to the highly heated rocks below.

c) The sudden injection of fluid rock into fractures or cavities formed in the mass of the volcano.

d) The slipping of the rock surfaces adjoining a fracture due to subterranean movements of the magma.

All of these are possible causes of volcanic earthquakes, and all four processes may be in action during or near the time of an eruption. The question we have now to consider is which cause

must be appealed to as offering the best explanation of the various phenomena of volcanic earthquakes.

For a long time the rending of the mountain mass has been regarded as a probable cause of volcanic earthquakes. G. P. Scrope wrote:

> It may very plausibly be suspected that each of the shocks by which the environs of a volcano are so repeatedly agitated, during, and previous to an eruption, is occasioned by the rending of some part of the solid frame-work of the mountain or its supporting strata, by the action of the force—resulting from the pressure in all directions of the liquid which is in communication with that elevated within the volcanic chimney. The prolongation or widening of a fissure previously formed would have the same jarring, or vibratory effect, as the creation of a new one.[1]

Nearly half a century later[2] Scrope repeated this paragraph with hardly any change except in the initial words, and these were altered to "there can be little doubt that," etc. That the fracturing of the mountain mass would be attended with considerable noise and some perceptible vibration cannot be disputed. Whether it is competent to produce earthquakes so strong as those which visit the southeastern flank of Etna or to give rise to the earthquake phenomena described above is less clear and remains, I think, unproved.[3]

Professor Omori ascribes volcanic earthquakes without explosions to the underground expansive force which produces cracks at the depth of a few kilometers; and those with explosions partly to the upward extension of the cracks, and partly, as regards the slow movements, to the outward pushing of the mountain mass consequent to the explosion.[4] If this be the case, it would seem that the earthquakes due to explosions would usually be of slight

[1] *Considerations on Volcanos* (1825), p. 155.

[2] *Volcanos* (1872), p. 163.

[3] The explanation has received support from well-known seismologists, among others from G. Mercalli (*Vulcani e Fenomeni Vulcanici in Italia* [1883], pp. 354–55), J. D. Dana (*Characteristics of Volcanoes* [1890], p. 22), F. Omori (*Bull. Imp. Earthquake Inv. Com.*, Vol. VI [1912], pp. 132–33), and A. Riccò (*Boll. Soc. Sis. Ital.*, Vol. XVI [1912], p. 32), but not from H. J. Johnston-Lavis (*Monograph of the Earthquake of Ischia* [1885], p. 92).

[4] *Bull. Imp. Earthquake Inv. Com.*, Vol. VI (1912), pp. 132–33.

intensity, for less than 1 per cent of those recorded on the Asama-yama were sensible to the observers on the mountain side. Here, again, we have no doubt a true cause of volcanic earthquakes, but one of unproved competence to produce the destructive shocks that visit the flanks of Etna and Monte Epomeo.

The sudden injection of lava into fissures and cavities would seem to be more effective and was regarded by the late Dr. H. J. Johnston-Lavis as the cause of the Ischian earthquakes. The theory may be held to account for the extreme localization of the earthquakes, for their repetition time after time in the same region, and for the brevity and sudden onset of the shock.[1]

Within the last few years the view has been gradually gaining ground that many of the stronger volcanic earthquakes are in reality tectonic earthquakes precipitated by volcanic action, that they are due not so much to the actual formation of fractures within the mass of the mountain as to slipping along pre-existing fractures. This view has the merit of connecting the earthquakes under extinct volcanoes such as the Alban Hills, with those, from which they do not in reality differ, under active or dormant volcanoes.

Professor G. Platania has shown that the Linera earthquake of May 8, 1914, was connected with a pre-existing fracture of the volcano, and he urges that subterranean movements of the magma have produced powerful tensions in the eastern region of Etna, by means of which the strata have been fractured, or pre-existing fractures have been enlarged, or the strata have slipped along them, and that these are the causes of the earthquakes.[2]

In some of the mining districts of Great Britain local earth-shakes occur which resemble the Etnean earthquakes so closely in their nature, and probably also in their origin, that it may be useful to give a brief description of one of them.

In Figure 9 are shown the isoseismal lines of an earth-shake which occurred at Pendleton (near Manchester) on November 25, 1905. The intensity of the shock was as high as 7 according to the Rossi-Forel scale (or 6 according to the Mercalli scale). The shock was felt over an area of 144 square miles. As the average

[1] *Monograph of the Earthquakes of Ischia* (1885), pp. 89–95.

[2] *Pubbl. dell'Ist. di Geog. Fis. e Vulcan. della R. Univ. di Catania*, No. 5 (1915), p. 41.

disturbed area of British earthquakes of the same intensity is 24,500 square miles, it is evident that the earthquake originated at a very slight depth. The mean direction of the longer axes of the isoseismal lines is N.37° W. That of the Irwell Valley fault near the epicenter (represented by the broken line on the map) is N.34° W. It would therefore seem probable that the

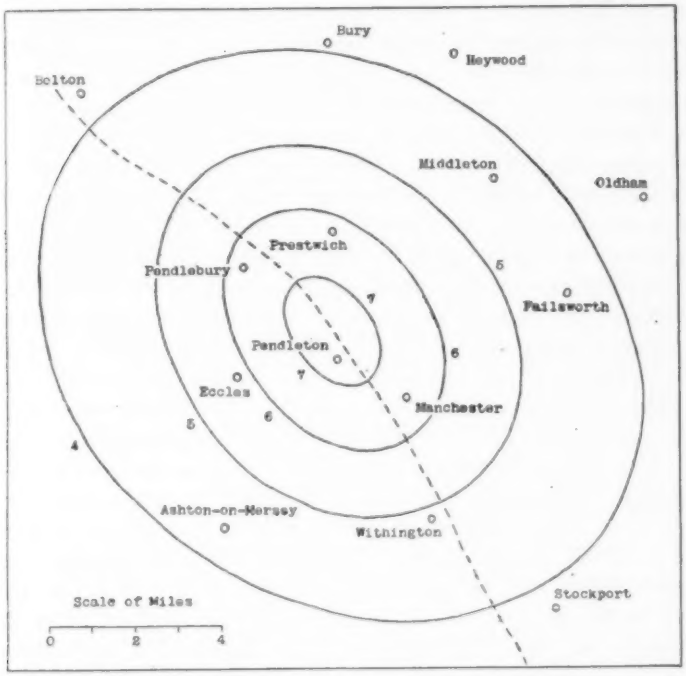


FIG. 9.—Map of Pendleton earth-shake of November 25, 1905

earth-shake was due to a slip along this well-known fault, and at a depth so small that it may well have occurred within the portion of the crust penetrated by the pit-workings at Pendleton. If this be the case, the fault-slip must have been precipitated, not by the natural and gradual growth of the fault, but by the removal of the rock which, it is known, has been effected right up to the

fault, or, possibly, by the pumping of water from the mine.[1] In other words, the Pendleton and other similar earth-shakes are of natural origin in so far as they are due to the growth of faults, but of artificial origin in that the slips are precipitated by mining operations.

An active volcano is coursed by many fractures, the majority of which are radial, but a few perimetric. If the rock mass or masses were in some way to be deprived of support, one mass would slide against the other, and the friction of the grating surfaces would give rise to an earthquake, not to be distinguished, except by its scale, from a true tectonic earthquake. In what way or ways could the rock mass be deprived of its support? Professor Platania suggests by underground movements of the magma,[2] and this might evidently be the case beneath active, and possibly beneath dormant, volcanoes. In all kinds of volcanoes, and especially in extinct volcanoes, another cause may be in operation, though acting much more slowly and giving rise therefore to infrequent shocks like those of Ischia. This is the gradual cooling of lava or heated rock beneath the fractured mass. And it should be noticed that the intensity of the resulting shock would not depend so much on the distance to which the support is withdrawn as on the area of the focus and on the weight of the rock displaced.

This theory, it will be seen, accounts for all the known phenomena of volcanic earthquakes—for their close connection in space and time with many eruptions, the shallowness of their foci and the great intensity of the shock within a limited area, the small size of the foci and the brief duration of the shocks, the occurrence of series of fore-shocks and after-shocks limited in duration and in space chiefly to the original focus, and, lastly, for the occurrence of volcanic earthquakes beneath dormant and extinct, as well as beneath active, volcanoes.

If this is the correct explanation of the cause of the more important volcanic earthquakes, it follows that such earthquakes are of tectonic origin in so far as they are due to the growth of faults, but of volcanic origin in that the slips are precipitated by present or past volcanic operations.

[1] *Geol. Mag.*, Vol. III (1906), pp. 171–76.

[2] *Pubbl. dell'Ist. di Geog. Fis. e Vulcan. della R. Univ. di Catania*, No. 5 (1915), pp. 1–2, 41.

Science & Industry
Department

THE STRATIGRAPHIC AND FAUNAL RELATIONSHIPS OF THE MEGANOS GROUP, MIDDLE EOCENE OF CALIFORNIA

BRUCE L. CLARK
University of California

CONTENTS

INTRODUCTION
HISTORICAL SKETCH
PURPOSE OF PAPER
THE MEGANOS GROUP IN THE VICINITY OF MOUNT DIABLO
- Meganos to the North of Mount Diablo
  - Stratigraphy and Lithology
  - Summary of Lithology of Section
  - Evidence for Unconformity between Meganos and Tejon Fauna from Meganos Beds
  - Comparison of Meganos and Tejon Faunas
- Meganos to South and Southeast of Mount Diablo Section Near East Edge of Concord Quadrangle
  - Lithology
  - Eocene Section to Southeast of Mount Diablo
    - Faunal Zones
    - Correlation

EOCENE SECTIONS IN SOUTHERN PART OF CALIFORNIA IN WHICH MEGANOS IS REPRESENTED
- The Eocene Section North of Coalinga
  - Unconformity
  - Fauna
  - Correlation
- Meganos at the South End of the San Joaquin Valley
  - General Statement
  - Area Studied
  - Faunal Evidence for Presence of Meganos
  - Unconformity
  - Lithology
  - Fauna of Type Tejon
- Eocene of Camulos Quadrangle
  - General Remarks
  - Lithology
  - Unconformity
  - Fauna
  - Correlation

FAUNA OF THE MEGANOS OF CALIFORNIA
CORRELATION
Correlation of Different Meganos Sections in Coast Ranges
Evidence for Correlation of Meganos of Coast Ranges with Beds of Siphonalia Sutterensis Zone Which Form a Part of the Ione Formation of the Foothills of the Sierra Nevada as Mapped by the United States Geological Survey
General Correlation
SUMMARY OF CONCLUSIONS

INTRODUCTION

The problems connected with the divisions of the marine Tertiary of the West Coast are complicated and their solutions difficult. This is due to the original conditions of deposition and to the magnitude of the crustal movements which have affected all the formations of this province, including the Pleistocene. The sediments were, for the most part, deposited in geosynclinal troughs, some of which appear to have been rather local. The deposits are of enormous thicknesses as compared with those of the same period in the Gulf and Atlantic Coast provinces. The aggregate thickness of the Tertiary of the West Coast exceeds 40,000 feet. Clastic materials predominate, and, over wide areas, the beds are either unfossiliferous or the preservation of the fossils poor, due to the leaching out of the original material of the shells. The destructive leaching is more general in the marine Tertiary of California than in that of Oregon and Washington. Crustal movements occurred along the West Coast more or less interruptedly throughout the Tertiary, and the groups of strata representing the major epochs of this time are, as a rule, separated by angular unconformities. The intense folding and faulting which accompanied these movements, together with the paucity and poor preservation of the faunas, have made the problems of correlation difficult, and it is only by detailed mapping, combined with careful paleontological work, that we can hope ultimately to arrive at the final solution. Due in part to these conditions and also to the fact that workers have been few, little has been accomplished toward distinguishing minor faunal divisions in the Tertiary of the West Coast, i.e., such faunal divisions as

might be found in a group of beds belonging to one epoch of deposition.

The foregoing remarks have especial application in connection with the faunas of the marine Eocene of the West Coast, where the larger part of the work of differentiating them remains to be done. Until very recently, one of the largest and most important breaks in the Tertiary of California, an unconformity in the Eocene deposits, was entirely overlooked, and a considerable part of the marine Eocene section of the state, as well as of Oregon and Washington, has been described in a sequence the reverse of the fact.

The fauna of Dr. R. E. Dickerson's Siphonalia sutterensis zone, regarded by him as a part of the Ione formation in the foothills bordering the western front of the Sierra Nevadas, has been regarded until recently as coming from the uppermost Eocene of the West Coast. The beds of this horizon can be shown to belong well down in the Eocene section, and strata of the same age are found in the Coast ranges of California overlain unconformably by beds of Tejon age. The latter formerly were considered to be the older.

In a recent paper the writer has given a summary of his work[1] on the Eocene in the vicinity of Mount Diablo, and has presented evidence to show that there are at least three major stratigraphic and faunal divisions in the Eocene of this region. Previously, only two such divisions had been recognized. The beds of the new division, to which the name Meganos Group was applied, formerly were considered a part of the Tejon.

As will be brought out below, the writer is not the first to advocate a threefold division of the Eocene of the West Coast. The important fact to be remembered in this connection is that, while the fauna of the Meganos had been recognized by previous workers in this field as belonging to a distinct division of the Eocene, the Ione of Arnold and Hannibal and of Waring, the stratigraphic position of this horizon was wrongly determined and, instead of representing the uppermost Eocene of the West Coast, this division comes below the Tejon, and is the middle of the three Eocene divisions as now recognized.

[1] Bruce L. Clark, "Meganos Group, a Newly Recognized Division in the Eocene of California," *Bull. Geol. Soc. America*, Vol. XXIX (1918), pp. 281–96.

HISTORICAL SKETCH

The most detailed work on the Eocene of the West Coast, since the time of Gabb, is that of Dickerson.[1] He recognized only two stratigraphic units as belonging to this period, the Martinez (Lower Eocene) and the Tejon (Upper Eocene). As the result of his studies of the so-called Tejon, he outlined four faunal zones, thought to occupy four successive horizons in that group. These, beginning with the lowest, were the Turbinolia zone, the Rimella simplex zone, the Belanophyllia variabilis zone, and the Siphonalia sutterensis zone. The first three zones were described from the Eocene section in the vicinity of Mount Diablo, and the fourth from the Eocene bordering the foothills of the Sierra Nevadas, the beds of which apparently form part of the Ione formation.

In the paper in which Dickerson first outlined his ideas of the faunal succession of the Tejon we find the statement:[2]

> A study of the relationship between zone 3, Mount Diablo region, and the Siphonalia sutterensis zone and their geographic position suggest that the uppermost strata of the Marysville Buttes and Oroville were deposited by a transgressing sea, and that only in favored places along the western borders of the Sierra have the latest Eocene sediments been preserved from erosion. Lava caps such as that of the older Basalt of South Table Mountain have preserved these youngest Tejon sediments which have heretofore been regarded as Ione.

The first writers to suggest that there are more than two distinct stratigraphic units or groups in the Eocene of the West Coast were Dr. Ralph Arnold and Mr. Harold Hannibal in a joint review of one of Dr. Dickerson's papers. These writers, in their study of the Eocene of Washington and Oregon, recognized three horizons, the Chehalis (at the base), Oliqua, and Arago or Ione (at the top) formations, all higher than the Martinez (Lower Eocene). Their Chehalis horizon they referred to the

[1] R. E. Dickerson, "Note on the Faunal Zones of the Tejon Group," *Univ. Cal. Pub. Bull. Dept. Geol.*, Vol. VIII (1914), No. 2, pp. 17–25; "Stratigraphy and Fauna of the Tejon Eocene of California," *Univ. Cal. Pub. Bull. Dept. Geol.*, Vol. IX (1916), No. 17, pp. 262–534, Pls. 36–46.

[2] R. E. Dickerson, "Note on the Faunal Zones of the Tejon Group," *Univ. Cal. Pub. Bull. Dept. Geol.*, Vol. VIII (1914), No. 2, p. 24.

same period of deposition as the typical Tejon; they did not recognize their Oliqua in California; the Arago formation was correlated with the Ione along the Sierra Nevada front. Arnold and Hannibal agree with Dickerson in placing the marine beds of the Ione as uppermost Eocene in age, but disagree in that they considered this horizon to belong to a distinct epoch of deposition. The following statements are taken from the paper of Arnold and Hannibal[1]:

> The writers have shown that in Oregon and Washington the Eocene may be divided into three faunal divisions, the Chehalis, Oliqua, and Arago or Ione formations. The Chehalis formation is characterized especially by *Venericardia hornii* Gabb, *Meretrix californica* Gabb, and an austral flora, the Oliqua formation by *Pecten* (*Chlamys*) *landesi* or *Venericardia hornii* Gabb and a tropical flora, and the Arago or Ione formation by *Turritella merriami* Dickerson, a form of *V. hornii* with obsolete ribs (var. *aragonia* A. and H.), and a tropical flora.
>
> The Arago or Ione beds represent a horizon younger than any Tejon recognized in the Tejon or Puget Basin. The Arago or Ione beds occurring as they do in basins distinct from those in which the Tejon series is developed, and being formed at a different period, must be treated as a distinct division of the Eocene.

Professor C. E. Weaver in his study[2] of the Eocene sections of the Cowlitz River Valley, Washington, the section studied by Arnold and Hannibal and where they described their Chehalis horizon as being below the Oliqua, disagrees with them as to the sequence. His stratigraphic study of this section apparently shows that the beds of the Oliqua formation are below those of the Chehalis; in other words, Arnold and Hannibal had their section upside down, a condition similar to that which existed in California.

The first published announcement by the writer of his discovery that there are three distinct groups of strata in the Eocene section of Mount Diablo appeared in a paper to which reference has been made.[3] It was not until this paper was in page proof

[1] Ralph Arnold and Harold Hannibal, "Dickerson on the California Eocene," *Science*, new series, Vol. XXXIX (1914), No. 1016, p. 607.

[2] C. E. Weaver, "Eocene of the Lower Cowlitz River Valley of Washington," *Proc. Cal. Acad. Sci.*, 4th ser., Vol. VI (1916), Nos. 1, 2, and 3, pp. 1–17.

[3] Bruce L. Clark, "Meganos Group, a Newly Recognized Division in the Eocene of California," *Geol. Soc. Amer.*, Vol. XXIX (1918), pp. 281–96.

that sufficient evidence was obtained to show that the fauna of the Meganos belongs to the same epoch of deposition as the Eocene marine beds in the vicinity of Marysville Buttes and at Table Mountain near Oroville. These beds generally have been referred to the Ione formation, and considered to represent the uppermost Eocene of the West Coast. A statement to this effect was included in a note at the end of the paper and in the summary of conclusions.

Briefly summarized, the most important results brought out in the paper last mentioned are: that in the Eocene of the region of Mount Diablo there are at least three groups instead of two, as was formerly believed; and that the beds of this newly recognized epoch of deposition come between those of the Martinez (Lower Eocene) and those of the Tejon (Upper Eocene). It was found that the Meganos Group on the north side of Mount Diablo has a maximum thickness of nearly three thousand feet. These beds previous to this time had been generally mapped as Tejon. The unconformity between the Meganos and the Tejon in this area is such a marked one that it may be classed as one of the major breaks in the Tertiary of the Coast ranges. In places there is a difference of from 15° to 20° in strike, and a maximum difference of about 18° in dip between the beds of the Meganos and those of the Tejon above. It was also the conclusion of the writer that there is a marked difference between the fauna found in the beds below and that in the beds above this unconformity, and finally that the beds of the Meganos Group have a fairly wide distribution throughout the Coast ranges of California, in some localities having been mapped as of Martinez, and in others of Tejon, age.

PURPOSE OF PAPER

The purpose of this paper is to sum up the results of more recent studies of other Eocene sections in different parts of the Coast ranges, including the Mount Diablo section, which was described somewhat in detail in the first paper. The most important contribution is the evidence which shows that there are three general divisions in the Eocene of California, namely, the Martinez, Meganos, and Tejon, each of which may be considered as belonging to a distinct epoch. After discussing the various Eocene sections, reasons will be given for correlating the beds referred to the Meganos

Science & Industry
Department

Group in these different areas in the Coast ranges with one another and with the marine Ione formation in the Sierra Nevada foothills,

FIG. 1.—Outline map of California. The numbers indicate the locality of the different sections discussed in this paper: (1) Mount Diablo region; (2) region to the north of Coalinga; (3) south end of San Joaquin Valley; (4) Camulus quadrangle; (5) Table Mountain in the vicinity of Oroville.

as mapped and described by Lindgren and Turner, not, however, including the type section of the Ione.

THE MEGANOS GROUP IN THE VICINITY OF MOUNT DIABLO

Mount Diablo is a much faulted anticline of which the Franciscan series forms the core. The Shasta-Chico series (Lower and Upper Cretaceous) is represented in this section by more than ten thousand feet of shales and sandstone, on top of which, on either side of the anticline, are Eocene strata having a maximum thickness of nearly four thousand feet. These beds in turn are overlain by beds referable to the Oligocene, Miocene, and Pliocene. The two Eocene sections, the one on the north side of the Mount Diablo anticline and the other on the south side, will be considered separately as their outcrops are disconnected.

MEGANOS TO THE NORTH OF MOUNT DIABLO

The type section of the Meganos is on the north side of the Mount Diablo anticline. In this paper, the description of that section is largely a repetition of the data presented in the former paper, but adds some details.

The section extends from about one mile to the west of the old coal-mining town of Nortonville, east and a little to the south of the eastern edge of Mount Diablo Quadrangle. These beds, including the Martinez, Meganos, and Tejon groups, dip to the north, the angle of dip varying from 15° to 40°. The greatest width of the outcrops is about two and a half miles.

Stratigraphy and lithology.—The beds of the Meganos Group in this area rest unconformably on those of the Martinez Group. This unconformity, as stated above, was first described by Dickerson.[1] The lower Tejon, as recognized at that time, is the base of the Meganos, as described in this paper. The Meganos beds in this area have a maximum thickness of about three thousand feet. The section may be roughly divided into five lithologic members. Beginning at the base, these will be designated divisions A, B, C, D, and E.[2]

[1] R. E. Dickerson, "The Stratigraphic and Faunal Relations of the Martinez Formation to the Chico and Tejon North of Mount Diablo," *Univ. Cal. Pub. Bull. Dept. Geol.*, Vol. VI (1911), No. 8, pp. 174–76.

[2] The lower part of this section, that is, the Martinez and divisions A, B, and C of the Meganos, are best exposed in the section just to the west and south of the old town of Stewartville. The upper Meganos beds are best exposed on the ridge just to the north of Deer Valley and to the north of that ridge. The best Tejon section is to be found in the vicinity of the old town of Nortonville; also a very good section may be seen in the vicinity of the old town of West Hartley.

Summary of lithology of section.—The outline below is a generalized section of the Eocene groups as found on the north side of Mount Diablo. The Martinez portion of the section is copied from Dickerson's paper.[1]

The conglomerates at the base of the Meganos Group, division A, because of their peculiar character are worthy of mention. In the vicinity of Stewartville great angular slabs of fossiliferous Chico sandstone, some of them five, six, or more feet in length, are associated with well-rounded quartzitic and igneous bowlders. With them are numerous smaller limestone and sandstone pebbles, derived either from the Martinez or the Chico, showing that these beds are a true basal conglomerate. When followed to the east these conglomerates thin out rapidly.

The shales of division C of the Meganos Group are especially noticeable in that they are so different from anything found in the Tejon series on either the north or south side of Mount Diablo. The dark color, the calcareous lenses and nodules, the surface slaking into small fragments, the presence of carbonaceous material, and the layers of coarse sandstone which separate the different shale members all are similar to lithological characters of the

OUTLINE OF EOCENE GROUPS

		Feet
Tejon Group	6. Clay shales with minor amount of sandstone	500
	5. Fine, buff-colored sandstone; in places hard, calcareous layers contain marine fossils	175
	4. Sandy shales; exposures poor; soil very red	175
	3. Light gray to white, angular-grained sandstones, coarse to medium in texture; cross-bedding common, with minor layers of chocolate-colored shales; two important coal layers	75–400
	2. Chocolate-colored shales, ashy in places, with thin lenticular layers of coarse sandstone; coal layer locally known as Black Diamond vein	50
	1. Conglomerate	0–20
	Unconformity	

[1] R. E. Dickerson, "Fauna of the Martinez Eocene," *Univ. Cal. Pub. Bull. Dept. Geol.*, Vol. VIII (1914), No. 6, p. 71.

			Feet
Meganos Group	E	Clay shales and sandstones at top, grades down into fine, massive, poorly indurated sandstone; exposures of the beds of this division are very poor	0–1,500
	D	Sandstone of medium texture; thin-bedded near bottom; more massive at top; yellow brown to gray in color with about 100 feet of cross-bedded sandstone, eolian type. The massive sandstones near top contain lenses of harder calcareous and fossiliferous sandstones	0–300
	C	5. Dark slate-gray shales; bedding planes fairly distinct; light calcareous nodules and lenses	0–230
		4. Sandstone, fine to coarse in texture; in places forms a grit; contains thin clay lenses; in places contains considerable carbonaceous material	110
		3. Dark slate-gray shales, similar to (1) and (5)	90
		2. Sandstone, medium to fairly coarse; weathers on surface a rusty brown; grains chiefly of quartz and mica	50
		1. Dark slate-gray clay shale; bedding planes indistinct; carbonaceous material abundant	75
	B	Coarse to medium fine, quartzitic, gray to gray-brown micaceous sandstones, with some fine conglomeratic layers which are fossiliferous in the eastern part of the area. Sandstone quartzitic at one horizon	700
	A	Heavy conglomerates; changes to sandstone along the strike; bowlders composed of quartzites, chert, limestone, and large angular slabs of sandstone, containing typical Chico (Upper Cretaceous) fossils	0–50
		Unconformity	
Martinez Group		5. Gray-green shale	300
		4. Gray-green glauconitic sandstone; Trochocyathus zitteli beds	50
		3. Fine-grained gray sandstone	200
		2. Shales and sandstones	100
		1. Brown conglomeratic sandstone; Meretrix dalli beds	50
		Total?	
		Unconformity	
Chico			

& Industry
Department

Knoxville shales (Lower Cretaceous or Upper Jurassic), as seen in certain sections of this general area. These sediments probably are shallow-water deposits, perhaps laid down in estaurine or partially land-locked basins.

Divisions B and D of the foregoing sections contain much biotite. This may be best seen in the sandstones, division D forming the ridge on the north side of Deer Valley. In certain layers, biotite is very abundant, the flakes being fairly large. Grains of feldspar also are present. In fact, the beds may be described as arkosic. The basal sandstones, division B, are also micaceous. The fauna obtained from these arkosic sandstones indicates a subtropical temperature; the lithology, taken in connection with the evidence for warm subtropical waters, possibly points to arid conditions on the land.

In the basal chocolate-colored shales of the Tejon, many impressions of leaves, rushes, and fossil wood are found. These beds will undoubtedly yield a large and well-preserved flora. These leaf shales were apparently laid down in marginal marine swamps. The presence of shells of the genus Corbicula, in a layer of sandstone in the shales, testifies to brackish or fresh-water conditions.

The most important of the coal beds of this region, and one mined throughout most of the area, is found near the top of these lower Tejon shales. In the vicinity of Nortonville this bed is known as the "Black Diamond Vein." It is reported to have a maximum thickness of about four feet. Above this coal seam at Nortonville is a sandy, conglomeratic bed varying from 1 to 3 feet in thickness, which is highly impregnated with limonite. Rush and leaf impressions were found also in this layer. The close association of this bed with the leaf shales and coal, together with the fact that the limonite deposit is limited to a definite layer over a considerable area, suggests a primary rather than a secondary origin.

The coarse, cross-bedded, light-colored sandstones immediately above the shale may well have been deposited under somewhat similar conditions. Two of the important coal-layers, the "Little" and "Clark" veins, mined for many years at Nortonville and Somerville, are found in these sandstones. The coal of the Clark vein, which is about two and one-half to three feet in thickness,

as exposed in the mine at Nortonville, is intercalated between the coarse, white, quartzitic sands without a trace of shale.

Evidence for unconformity between Meganos and Tejon.—The most important evidence for unconformity between the Meganos and the Tejon is the great difference in strike between the beds of the two horizons, seen at numerous localities; this is very noticeable at the coal mine at Stewartville, where the difference approximates 15° (Fig. 1). The basal sandstone of division D is here in contact with the Tejon, the thickness of the sandstone being approximately 150 feet. Followed west of Stewartville, the sandstone disappears and the basal beds of the Tejon rest directly on the upper dark-colored shale (division C), and a little west and south of Nortonville the Tejon rests on the first sandstone member below the top of division C. Southeast of Stewartville the sandstone of division D emerges from beneath the Tejon and forms the ridge north of Deer Valley; the shaly sandstones and shales of division E also appear, and within 3 or 4 miles of Stewartville show their maximum thickness, 1,500 feet. In the canyon south of the Star Mine, not much more than a mile from Stewartville, the upper shales of division E are well developed.

Besides this difference in strike and the rapid emergence of the upper Meganos beds from beneath the Tejon, a marked difference in dip was noted at a number of localities southeast of Stewartville. In general it appears that there is a difference in dip between the two horizons throughout the entire length of the area. At the west end of the area southwest of Nortonville there is a maximum difference in dip of 18° between the upper Meganos beds and those of the lower Tejon. In the vicinity of Stewartville the difference approximates only about five degrees, while in the vicinity of West Hartley the difference is between 15° and 20°.

In the western part of the area under discussion, there are heavy conglomerates at the base of the Tejon which in some places have a thickness approximating 20 feet. Here they rest on the dark shale of division C, and at a number of localities a sharp irregular contact was seen, the bedding planes of the shale being cut off by the conglomerate. It is a noticeable fact, also, that there is considerable carbonaceous material at the contact. In

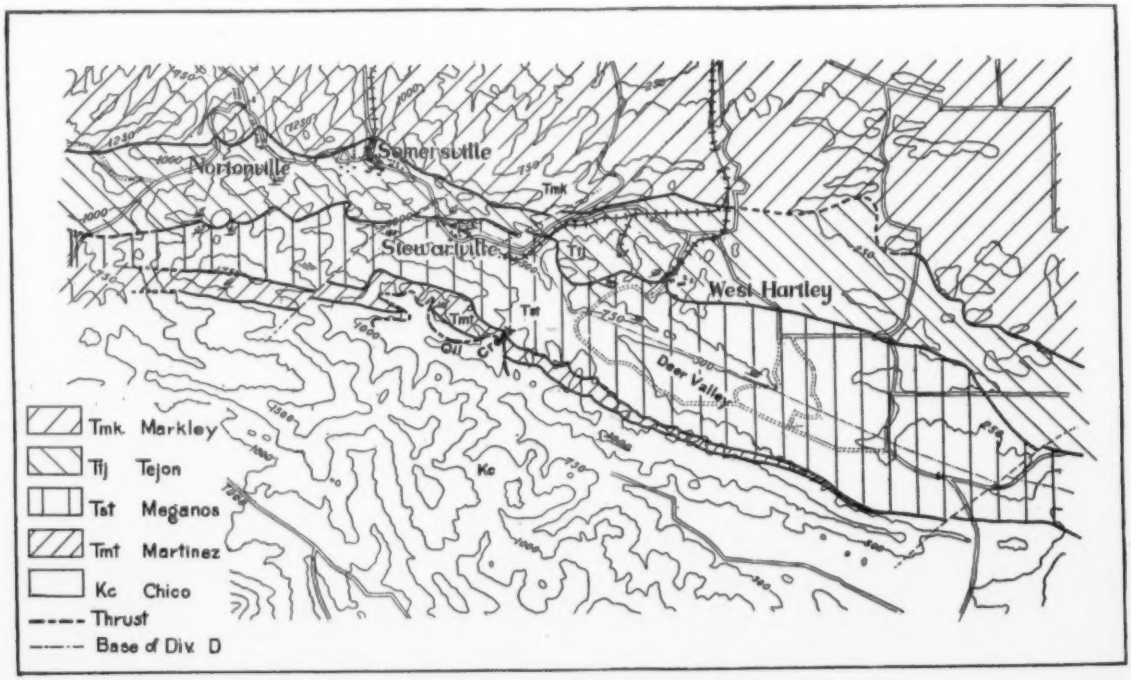


FIG. 2.—Areal map of the Eocene deposits to the north of Mount Diablo

the vicinity of Stewartville and West Hartley the conglomerates disappear and the chocolate shales at the base of the Tejon rest on the shales and shaly sandstones of division E of the Stewartville, making it impossible to find a sharp contact anywhere.

Fauna from Meganos beds.—The following is a preliminary list of the Meganos species obtained from the section described above. The majority of them came from the sandstone division D, a few species from the fine sandstones of division E, and a few from the basal sandstones near the eastern border of the Mount Diablo Quadrangle extending into the Byron Quadrangle to the east:

PELECYPODA

Acila gabbiana Dickerson
Antigona, 2 n. sp.
Arca hornii Gabb, n. var.
Avicula, sp.
Cardium brewerii Gabb, n. subsp.
Cardium marysbillensis Dickerson
Corbula diletata Waring
Corbula, n. sp.
Crassatellites, 2 n. sp.
Dosinia, n. sp.
Diplodonta cretacea Gabb
Glycimeris major Stanton, n. var.
Leda gabbi Conrad
Leda (cf. *alaeformis* Stanton)
Marcia (?) *conradi* Dickerson
Martesia, n. sp.
Macrocallista, n. sp. aff. M. Conradi Gabb
Modiolus ornatus Gabb
Ostrea, sp.
Psammobia, n. sp.
Periploma, n. sp.
Solemya, n. sp.
Solen, n. sp.
Solen, n. sp.
Spisula tejonensis Dickerson
Spisula (cf. *merriami* Dickerson)
Spisula, n. sp.
Tellina longa Gabb
Tellina, sp.
Tellina rémondii Gabb
Tivela, n. sp.
Venericardia planicosta (cf. var. *merriami* Dickerson)

GASTROPODA

Acmaea, n. sp.
Actaeon, 3 n. sp.
Brachysphingus, 2 n. sp.
Calliostoma, n. sp.
Chrysodomus, 2 sp.
Calyptraea excentrica Gabb
Cancellaria Stantoni Dickerson
Cancellaria, n. sp.
Clavilithes, n. sp.
Conus, sp.
Cylichna, n. sp.
Cypraea, n. sp.
Exilia, sp.
Ficopsis, n. sp.
Fusinus, n. sp.
Galeodea sutterensis Dickerson
Haminea, n. sp.
Natica gesteri Dickerson
Natica hornii Gabb
Natica, n. sp.
Neptunea, n. sp.

Odostomia, n. sp.
Oliva, 2 n. sp.
Phos martini Dickerson
Siphonalia sutterensis Dickerson
Scaphander, n. sp.
Solarium, 2 n. sp.
Terebra, n. sp.
Turris, 5 n. sp.
Turris monolifera Cooper
Turritella, 2 n. sp.
Turritella merriami Dickerson
Whitneya, n. sp.

SCAPHODA

Dentalium (cf. *cooperi* Gabb)
Dentalium, n. sp.

CEPHALOPODA

A Nautiloid, genus indet.

ANTHOZOA

Turbinolia, 2 sp.
Flabellum, n. sp.
Stephanophyllia, n. sp.
Dendrophyllia (?), n. sp.

Comparison of Meganos and Tejon faunas—Up to the present time 68 species have been reported from the Tejon beds on the north side of Mount Diablo. Most of these were listed either by Stanton or Dickerson in the papers already referred to. This upper fauna, referred by Dickerson to his Balanophyllia zone, contains a number of the species which are typical of the type section of the Tejon, such as *Meretrix hornii* Gabb, *Meretrix tejonensis* Dickerson, *Conus remondii* Gabb, *Ficopsis* cf. *cowlitzensis* Weaver, *Turritella uvasana* Conrad, *Turritella uvasana bicarnata* Dickerson.

The fauna of the Meganos as obtained from the type section described above is very different from that of the Tejon. Not more than five of the more than seventy determined species have been found in the Tejon as recognized in this section or known Tejon section. The presence of such described species as *Phos martini* Dickerson, *Siphonalia sutterensis* Dickerson, *Turritella merriami* Dickerson, *Schizaster diabloensis* Kew, together with a fairly large number of undescribed species, is the evidence for correlation of these beds with the Eocene of Marysville Buttes and Oroville, which contain the fauna of Dickerson's Siphonalia sutterensis zone, and with the beds referred to the Meganos on the south of Mount Diablo and the other Meganos sections described in this paper.

MEGANOS TO SOUTH AND SOUTHEAST OF MOUNT DIABLO

SECTION NEAR EAST EDGE OF CONCORD QUADRANGLE

When the first paper on the Meganos was published, comparatively little work had been done on the Eocene section south of the Mount Diablo anticline. A brief description was given in that paper of the beds exposed near the east border of the Concord Quadrangle which joins the Mount Diablo Quadrangle on the west. Here a typical Meganos fauna was found stratigraphically below beds containing a Tejon fauna.

Lithology.—In this section the Meganos beds have an approximate thickness of 2,000 feet. At the base there is between 150 and 200 feet of medium-fine yellow-brown sandstone beginning with about 20 feet of basal conglomerate which contains angular bowlders of fossiliferous Chico (Upper Cretaceous) sandstone, together with angular fragments of shale which is very similar to that found immediately below the contact. The upper 1,800 feet of the Meganos consists principally of dark-colored shales, fine shaly sandstone, and fine sandstone. Some of these shales are almost black and contain considerable lignitic material; they are identical in character with the dark-colored shales in the Meganos north of Mount Diablo.

There is a very marked lithological change between the Tejon beds of this section and those of the Meganos. The Tejon beds consist of 2,000 feet of massive, buff-colored quartzose sandstones which weather into cavernous bluffs on the north side of Pine Canyon a little farther east. At what appears to be the base of the Tejon is a narrow band of fine conglomerate made up of quartz and black and red chert, together with angular fragments of shale similar to the shale member immediately below.

Coal has been found at a number of localities in the basal beds of the Tejon, indicating the same general conditions as those recorded by the sediments on the north side of the mountain. In the sandstones near the base the species *Balanophyllia variabilis*, a coral which is common in the beds above the coal in the Tejon on the north side of Mount Diablo, was found in abundance.

This species is one of the most important markers of Dickerson's Balanophyllia variabilis zone.[1]

EOCENE SECTION SOUTHEAST OF MOUNT DIABLO

The Meganos and Tejon beds of the section just described can be followed continuously eastward, barring some cross-faulting, from the area on the Concord Sheet, to that in the Mount Diablo Quadrangle in which Dickerson made his study. In this section data were obtained for the establishment of three of his faunal zones.

The typical Tejon is represented throughout this area by heavy, massive, buff-colored quartzose sandstones, the outcrops of which form a prominent feature of the landscape. The Meganos beds of the more eastern area are composed for the most part of shale and shaly sandstone, with sandstones at the base, a section which is very similar to that just described, about ten miles to the west.

Detailed mapping has failed to show any marked difference in dip and strike between the Meganos and the Tejon in this southern area, such as occurs to the north of the mountain. At a few localities there is an apparent difference in dip between the beds of the two horizons; this, however, could not be verified with certainty, the division being recognized by a sharp change in lithology, and by faunal evidence.

Faunal zones.—The locality at which Dickerson did most of his work in the "Tejon" of Mount Diablo is southeast of the mountain, in the vicinity of Cave Point and Riggs Canyon. Dickerson divided his (so-called) Tejon into three horizons, the faunas of which were referred to as: (1) the Turbinolia zone; (2) the Rimella simplex zone; and (3) the Balanophyllia variabilis zone.[1]

[1] R. E. Dickerson, "Stratigraphy and Fauna of the Tejon Eocene of California," *Univ. Cal. Pub. Bull. Dept. Geol.*, Vol. IX (1916), No. 17, pp. 373–79.

[2] In the former paper referred to above, the writer stated that in this section thereis a marked difference in strike between the Meganos beds and those of the Tejon, and the difference was taken as one of the evidences of the unconformity between the beds of these two horizons. Later work, however, has shown that this apparent difference in strike is, in part at least, the result of faulting. Also it was stated that to the east of this area the Meganos disappeared due to this unconformity. At that time the writer had not recognized that the so-called Tejon beds to the east, as described by Dickerson, were in part Meganos.

Correlation.—Later work has shown that the faunas of the Turbinolia zone and the Rimella simplex zone belong to the Meganos epoch, while the fauna of the Balanophyllia zone represents typical Tejon.[1] A fairly large number of what are believed to be distinctive markers of the Meganos have been found in the beds referred to the lower two zones just mentioned. A few of the more important of these species which have been found in other Meganos localities and may be considered as markers of that horizon are: *Schizaster diabloensis* Kew, *Turbinolia pusillanima* Nomland, *Venericardia* cf. *merriami* Dickerson, *Trochocyathus imperialis* Nomland, *Ancilla* (*Oliverata*) *California* Cooper, *Rimella*, n. sp., *Siphonalia sutterensis* Dickerson, *Turritella merriami* Dickerson, *Turritella andersoni* Dickerson. In the beds representing the other zone, equally good evidence was obtained for correlating them with the typical Tejon.

It is interesting to note at this point that at the time Dickerson wrote his paper "Stratigraphy and Fauna of the Tejon Eocene of California," Arnold, Hannibal, and W. A. Waring correlated the Tejon in the vicinity of Mount Diablo with the Ione as recognized by them, which they recognized as an epoch distinct from and later than the Tejon. The faunas collected by Arnold and Hannibal, and by Waring from the Mount Diablo region appear to have come from the basal beds of the Eocene to the south and southeast of the mountain, Dickerson's lower Tejon recognized by the writer as Meganos. The locality from which the original so-called Ione marine fauna was obtained by these writers, with which they correlated the Mount Diablo fauna, was the south side of Table Mountain. This may be considered the type of Dickerson's Siphonalia sutterensis zone, the fauna of which he thought represented the highest horizon of the West Coast Eocene. This horizon is here placed well down in the Eocene, below the Tejon. Thus Arnold and Hannibal and Waring agree with the writer in their correlation of these lower beds in the Eocene section on the south side of Mount Diablo with the Eocene of Oroville, but they erred in regarding their Ione the uppermost Eocene of the Pacific Coast. They erred with Dickerson in their interpretation

[1] The species listed by Dickerson as Rimella simplex is a new species.

Mines & Industry
Department

of the sequence, and if they had made sufficient collections, would undoubtedly have recognized the proper sequence.

EOCENE SECTIONS IN THE SOUTHERN PART OF CALIFORNIA IN WHICH THE MEGANOS GROUP IS REPRESENTED

In my first paper on the Meganos Group, reference was made to two Eocene sections in southern California, in which Meganos beds are present. One of these sections is north of Coalinga, on the west side of the San Joaquin Valley; and the other is in the vicinity of Simi Hills, Ventura County. During the summers of 1918 and 1919 several weeks were spent in studying these sections and also the Eocene at the south end of the San Joaquin Valley, where the type section of the Tejon is situated. The results of this work showed conclusively that beds of both Meganos and Tejon age are present in all of these areas, and that there is in each an unconformity separating the strata of these two series. The faunas from the Meganos of these three areas are very similar, containing in common a considerable number of highly ornamented species.[1]

THE SECTION NORTH OF COALINGA

Unconformity.—The unconformity between the Tejon and Meganos groups, in the Eocene section north of Coalinga, has been described by several writers,[2] most of whom considered the beds below the unconformity to be of Martinez age, while the beds above were considered to be Tejon. Dickerson[3] expressed the opinion that the Turritella andersoni beds, those here referred

[1] One of the most common species found in the Meganos of southern California is *Turritella andersoni;* in the past these beds have sometimes been referred to as the Turritella andersoni beds. This species is also found in the Meganos to the southeast of Mount Diablo.

[2] J. A. Taff, "Eocene of the Coalinga–Cantua District, Fresno County, California," *Proc. Pal. Soc. America* (1913), p. 127; E. T. Dumble, "Notes on Tertiary Deposits near Coalinga Oil Field and Their Stratigraphic Relations with the Upper Cretaceous," *Jour. Geol.*, Vol. XX (1912), pp. 28–37; Robert Anderson and Robert Pack, "Geology and Oil Resources of the West Border of the San Joaquin Valley, North of Coalinga, California," *U.S. Geol. Survey, Bull. 603* (1915), p. 66; R. E. Dickerson, "Stratigraphy and Fauna of the Tejon Eocene of California," *Univ. Cal. Pub. Bull. Dept. Geol.*, Vol. IX (1916), No. 17, pp. 382–87.

[3] R. E. Dickerson, *Univ. Cal. Pub. Bull. Dept. Geol.*, Vol. IX (1916), No. 17, pp. 382–87.

to the Meganos Group, were of Tejon age. My conclusion was stated as follows:[1]

> After studying the fauna from the Turritella andersoni beds, the same material on which Dickerson based his conclusions, the writer was impressed with the fact that there are so few typical Tejon species in this fauna. He does not agree with a number of the specific determinations that Dickerson made, as given in his list from locality 1817. Evidently Dickerson did not consider the possibility of there being a third group coming in between the Martinez and the Tejon, and that if this were so, one might well expect to find a larger number of species bridging the gap between this intermediate horizon and the Tejon than the gap between the Martinez and the Tejon.

Study of the Eocene series to the north of Coalinga showed conclusively that there is an unconformity in this section, and that the fauna obtained from above this contact is that of the typical Tejon, while the fauna below is referable to the Meganos. It is not the purpose in this paper to describe the lithology of the Eocene of this section except incidentally. Anderson and Pack of the United States Geological Survey have already described the lithology of this section[2] in detail. Accompanying their paper is a geologic map of the area. They referred the beds below the contact to the Martinez, and those above to the Tejon. The writer followed this contact nearly 20 miles, from a point near the old station of Oil City, to the Arroyo Honda near the west border of the Coalinga Quadrangle. Good evidence of an unconformable relationship was found along the entire distance.

As seen between the southern end of Domengine Creek and Cantua Creek (Coalinga Quadrangle), the upper beds of the Meganos consist of a white sandstone, which was mapped by Anderson and Pack as a part of the Tejon.[3] The contact between the Meganos and the Tejon comes in between this sandstone and somewhat similar sandstones of the Tejon. It is, as a rule, marked by a conglomerate, and is irregular at numerous

[1] Bruce L. Clark, "Meganos Group, a Newly Recognized Division of the Eocene of California," *Bull. Geol. Soc. Amer.*, Vol. XXIX (1918), No. 2, p. 294.

[2] Robert Anderson and Robert Pack, "Geology and Oil Resources of the West Border of the San Joaquin Valley, North of Coalinga, California," *U.S. Geol. Survey, Bull. 603* (1915), p. 66.

[3] Anderson and Pack, *op. cit.*, p. 66.

Science & Industry
Department

localities. The sandstones below the contact, due to the unconformity, thicken and thin very noticeably along the strike. Also, at a number of localities the lower sandstones show a dip and strike appreciably different from those of the Tejon beds above. While these differences amount at the most to only a few degrees, it is sufficient to cause the lower sandstone layers to be cut off obliquely, and on the cliff sections they are seen to abut against the basal beds of the Tejon (Figs. 3 and 4). Other evidence of this unconformity is the fact that numerous bowlders of sandstone, derived from the Meganos beds below, are found in the conglomerate at or near the base of the Tejon (Figs. 4 and 5).

Fauna.—An invertebrate fauna,[1] listed by Dickerson, was obtained from the beds above the unconformity just noted. It is, apparently, of typical Tejon age, containing a considerable number of highly ornamental molluscan species which have not been found in the Meganos.

The fauna obtained from the beds below the unconformity, the "Turritella andersoni beds," is essentially the same as that of the Meganos in the region of Mount Diablo, the ends in both places containing a fairly large number of highly ornamented species in common. The recognizable described species, which have been obtained from this portion of the section, are indicated in the list on page ooo.

Correlation.—Dickerson correlated the Turritella andersoni beds, just mentioned—the Martinez (?) as mapped by Anderson and Pack of the United States Geological Survey—with the lowest Eocene southeast of Mount Diablo (see p. ooo), the horizon of his Turbinolia zone. He believed that the beds of this horizon were older than the lowest beds in the type section of the Tejon. The writer agrees with both of these conclusions.

MEGANOS AT THE SOUTH END OF THE SAN JOAQUIN VALLEY

General statement.—An important problem which presented itself in connection with the differentiation of the Meganos from the Tejon, was whether any portion of the type section of the

[1] See list given under University of California locality 672. R. E. Dickerson, "Stratigraphy and Fauna of the Tejon Eocene of California," *Univ. Cal. Pub. Bull. Dept. Geol.*, Vol. IX (1916), No. 17, p. 430.

FIG. 3.—Diagrammatic sketch of panorama shown in Fig. 4, illustrating the unconformable contact between the Meganos and the Tejon. The beds, as shown in the view, are dipping into the hill at an angle of close to 30°.

Tejon might be referable to this newly recognized series and, if so, how much of the fauna, previously considered Tejon, belonged in reality to this other division.

The higher mountains immediately south of the San Joaquin Valley, the rocks of which are principally granites and older metamorphics, connect the Sierra Nevadas with the eastern Coast ranges. The hills immediately north of the granitic area and bordering the southern end of the valley are of Tertiary sediments, together with a minor amount of volcanic rock. The oldest unmetamorphosed sediments in this general section are of Eocene age, the outcrops of which may be traced in a narrow belt around the southern end of the valley for a distance of more than thirty miles. These Eocene beds rest on the granites and are overlain unconformably by beds of Oligocene or Lower Miocene age. The Tertiaries in this region have been folded and faulted and the beds as a rule dip at a high angle; in fact, in some localities the beds are overturned to the north, toward the valley, and the sequence is complicated by thrusting. This, however, is not true of the Eocene strata which border the granites. Here, along a narrow east-west belt for a distance of more than twenty miles, is found a normal section. The type section of the Tejon, in Grape Vine Canyon (the Spanish name is Canada de las Uvas) about thirty miles due south of Bakersfield, comes within this belt.

During the summer of 1919, ten days were spent in mapping and studying these Eocene rocks. While much more work remains to be

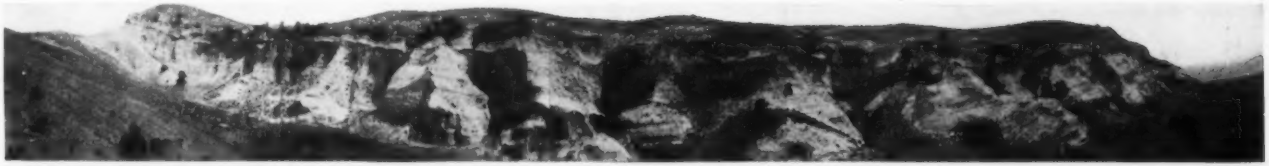
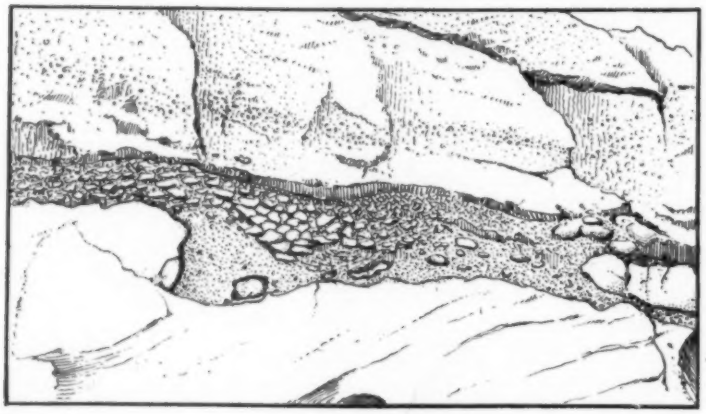


FIG. 4.—A panoramic view of cliff section composed of Meganos and Tejon rocks, as seen immediately south of divide between Cantua and Salt creeks, Coalinga Quadrangle. The unconformable contact is near the top of the cliff a little below the line of vegetation. Photographed by Mr. Anthony Folger. See diagrammatic sketch of this section in Fig. 3.

Science & Industry Department

a



b

FIG. 5.—(*a*) A close view of the unconformable contact between the Meganos and the Tejon outcrops at a locality about one mile north of Cantua Creek, Coalinga Quadrangle. Photographed by Mr. Anthony Folger. (*b*) Diagrammatic sketch of contact shown in photograph above. The pebbles and bowlders in the conglomerate were derived from the sandstone immediately below.

done before this section is known in detail, enough data were obtained to show conclusively that both Meganos and Tejon are present. The portion of the Eocene outcrops studied extends from San Emigdeo Canyon east to Live Oak Canyon, the latter being the first canyon to the east of Grape Vine Canyon (see map on p. 151).

Faunal evidence for presence of Meganos.—Just to the east of San Emigdeo Canyon fossiliferous beds were found near the base of the section not far above the granite, and from these beds a good Meganos fauna was obtained.

The following is the list of species from this locality:

Cardium, n. sp.
Cardium cf. *marysvillensis* Dickerson
Glycimeris, sp. (?)
Leda fresnoensis Dickerson
Meretrix, n. sp.
Psammobia, n. sp.
Tellina, n. sp.
Venericardia, n. sp.
Amauropsis alveata Conrad
Calyptraea cf. *excentrica*
Natica hannibali Dickerson
Rimella, n. sp.
Turritella, n. sp.
Scaphander, n. sp.
Seraps erratica (Cooper)

This fauna contains several of the distinctive forms of the Meganos, such as *Leda fresnoensis* Dickerson, *Venericardia* n. sp., *Rimella* n. sp., *Natica hannibali* Dickerson, *Turritella* n. sp. Probably the most distinctive species in this fauna is the *Rimella* n. sp., which is very common in beds of the Meganos from Mount Diablo to southern California.

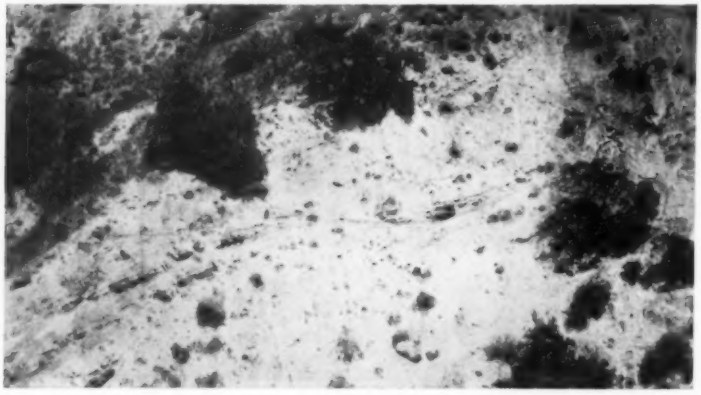
Unconformity.—These fossiliferous Meganos beds were found to rest unconformably below others containing a typical Tejon fauna, the latter connecting directly with the outcrops of the typical Tejon of Grape Vine Canyon.

One of the localities where the unconformable contact between the Meganos and the Tejon may be seen distinctly is about one-eighth of a mile back of the old Douglas ranch-house in the main canyon of San Emigdeo Creek.[1] Here the contact is beautifully exposed on the side of the canyon. There is a difference in dip between the two series of as much as 10° A basal conglomerate containing fossiliferous bowlders derived from the beds below was

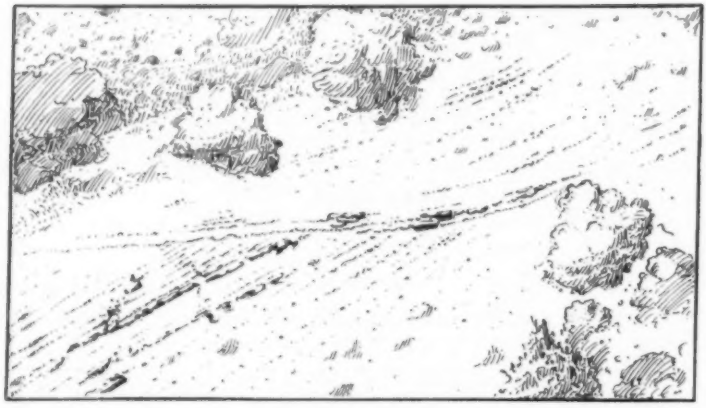
[1] Near south edge of NW. ¼, Sec. 5, T. 9 N., R. 21 W.

found along the contact (Fig. 6). The unconformity is also shown on the map (Fig. 7, p. 151).

At the locality just mentioned the Meganos beds have a thickness of less than 15 feet, and not more than 300 feet to the west



a



b

FIG. 6.—(*a*) A close view of the unconformable contact between the Meganos and Tejon outcrops as seen on the east side of San Emigdeo Canyon. (*b*) Diagrammatic sketch of contact shown in photograph above.

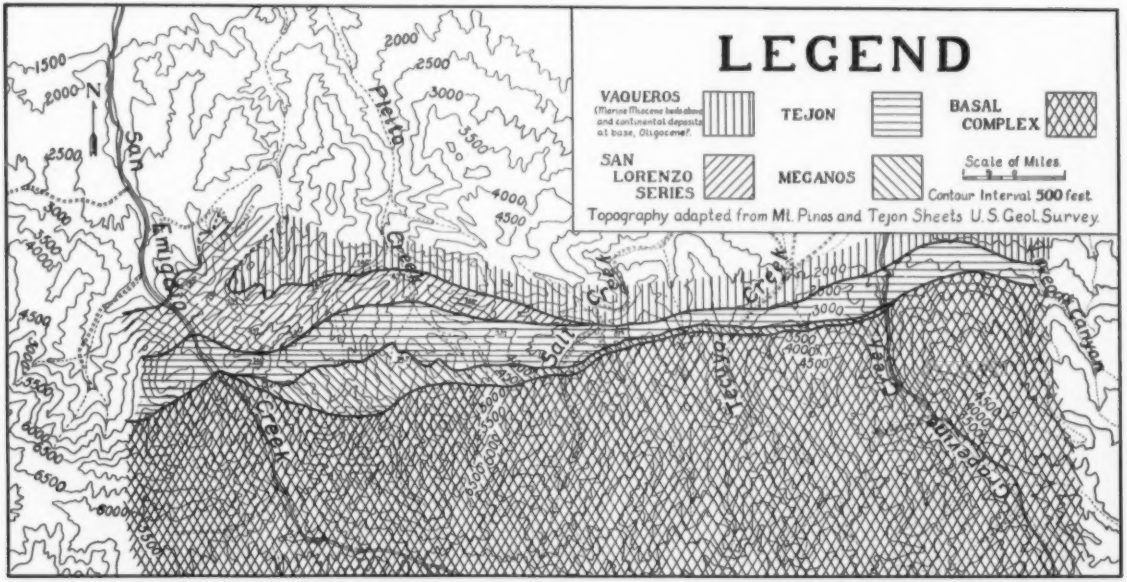


FIG. 7.—Areas map, showing distribution of Eocene and Oligocene outcrops at the south end of the San Joaquin Valley

the basal conglomerate of the Tejon rests on the granite. Just back of the ranch-house, a little farther west, a remnant of the basal Meganos sandstone outcrops below the basal conglomerate. Here the unconformity is evident. Traced east of this locality, the Meganos beds are found to thicken rapidly, reaching their maximum thickness near the head of Pleito Canyon about three miles to the east, where the Meganos beds have an estimated thickness of more than one thousand feet. As shown on the map, these beds thin out rapidly farther east, and in the canyon of Salt Creek, only a little more than four miles distant, their thickness probably is not more than one hundred feet. The conglomerate of the basal Tejon was traced to Tecuya Creek in the next large canyon east of Salt Creek. In Grape Vine Canyon the basal conglomerate of the Tejon was found to be separated from the granite by about twenty-five feet of unfossiliferous, coarse arkosic sandstone, together with a few feet of dark shales.

Thus the beveled Meganos is transgressed by the Tejon from west to east in the vicinity of Grape Vine Canyon, only a very small part of the Meganos being left, and in the next canyon to the east of Live Oak Canyon the Meganos beds fail to appear.

Lithology.—The Meganos outcrops are best exposed between Pleito and San Emigdeo canyons. The basal beds consist of several hundred feet of fairly indurated, coarse, reddish-gray arkosic sandstone. The upper part of the section is composed principally of sandy shales and platy shaly sandstone.

The Tejon beds of this region have a thickness of a little more than two thousand feet. The thickness in the vicinity of Grape Vine Canyon was estimated to be about twenty-four hundred feet. In the vicinity of this canyon the beds consist principally of medium-fine buff-colored sandstone, with lenticular harder, calcareous fossiliferous layers. This section, as already described by Anderson and Dickerson, is very uniform in lithology. To the west these beds become finer, and in the vicinity of San Emigdeo Canyon the larger part of the section might be described as a mudstone. In places lenses of conglomerate are found with the finer sediments, and at one horizon not very far from the base is a heavy layer of conglomerate that can be traced

for a considerable distance. It would appear that the Tejon beds in this last general locality may be delta deposits rather than typical marine deposits, such as those to the east in the vicinity of Grape Vine Canyon. This is borne out by the paucity of the fauna as well as by the lithology.

Fauna of the type Tejon.—The faunas obtained from different horizons in the type section of the Tejon, as found in Grape Vine Canyon, were studied by Dickerson. The invertebrate species were listed and a number of new species described by him.[1] Dickerson's conclusion, with which the writer agrees, was that the fauna obtained from the various horizons in the type Tejon, taken as a whole, is a unit. It has already been pointed out that Dickerson believed that these beds were somewhat younger than the Turritella andersoni beds at Coalinga or his lower Tejon from the south side of Mount Diablo, which beds of both localities are referred by the writer to the Meganos. In discussing this fauna, he says:[2]

> Beds about three hundred feet above the base (University of California locality 458) yielded an excellent fauna. This fauna, however, does not differ essentially from that of the beds higher in the section. The faunas from several other localities which are listed below do not differ materially from one another, but appear to represent one phase only. This faunal unity is in consonance with the sedimentary record as Anderson described it. . . . .
>
> The writer is in complete agreement with Anderson's view as expressed here in relation to the type Tejon. However, beds both higher and lower than the Eocene of Canada de las Uvas occur in other parts of the state, notably in the vicinity of Mount Diablo, along Cantua Creek, Coalinga Quadrangle, and at the Marysville Buttes.

As quoted in the paragraph above, Dickerson recognized that the fauna of the type Tejon was higher than that from the Lower Eocene beds on the south side of Mount Diablo, and higher than his so-called lower Tejon at Coalinga, the Turritella andersoni beds, which latter beds are here referred to the Meganos Group. He correlated the fauna of the type Tejon with that of his Rimella

[1] R. E. Dickerson, "Fauna of the Type Tejon; Its Relation to the Cowlitz Phase of the Tejon Group of Washington," *Proc. Cal. Acad. Sci.*, Vol. V (1915), No. 3, pp. 33–98.

[2] R. E. Dickerson, *op. cit.*, p. 40.

simplex zone. With this correlation I do not agree. As stated in the discussion on p. 000, the species *Rimella simplex* has not been found in the vicinity of Mount Diablo. The specimens from the south side of Mount Diablo, determined as such by Dickerson, belong to a new species which appears to be characteristic of the Meganos horizon. The so-called Rimella simplex beds of Mount Diablo come within the Meganos part of the section, and contain the typical species of that horizon.

EOCENE OF THE CAMULOS QUADRANGLE,[1] VENTURA COUNTY

General.—The fourth Eocene section studied during the summer of 1918 is that of the Camulos Quadrangle of Ventura County, California. The Eocene outcrops are found on both sides of the Simi Valley, the best and most complete section being in the hills on the south side of the valley, the strike of the beds almost paralleling the valley in an east-and-west direction. The late W. A. Waring described and mapped the geology of this area.[2] He recognized two Eocene divisions in this section, the Martinez and the Tejon, stating that apparently the Martinez (Lower Eocene) graded up into the Tejon. The fauna figured and described by him in his paper as Tejon is that of the Meganos. However, the Tejon also is represented in this section resting unconformably upon the Meganos.

Lithology.—This general area is being mapped and described by Dr. William S. W. Kew of the United States Geological Survey. According to him, the maximum thickness of the beds here referred to the Meganos is about three thousand five hundred feet. They consist principally of bluish-gray shales and shaly sandstones. Massive conglomerates are found near but not at the base. No sharp line of division between the Martinez and the Meganos has been found in this section. This, very possibly, is due to the lack of sufficient detailed work. The Tejon here consists of a series of about one thousand five hundred feet of coarse sand-

[1] The eastern half of Camulos Quadrangle comprises the Santa Susana and Calabasas quadrangles.

[2] W. A. Waring, "Stratigraphic and Faunal Relations of the Martinez to the Chico and Tejon of Southern California," *Proc. Cal. Acad. Sci.*, 4th ser., Vol. VII (1917), No. 4, pp. 41–124, Pls. 7–16.

Science & Industry
Department

stones, cross-bedded sandstones, and conglomerates. Above this is a great thickness of land-laid beds which are generally correlated with the Sespe formation.

Unconformity.—The contact between the Tejon and Meganos of this section is marked by conglomerates and conglomeratic sandstones. At a number of localities true basal conglomerate was found. The unconformity between the beds of these two horizons is also brought out by the mapping. On the south side of the Simi Valley near its east end the Meganos beds have a thickness of about one thousand five hundred feet; traced westward they thin out rapidly and near the west end of the valley disappear, due to overlap of the Tejon beds. This disappearance of the Meganos beds takes place in a very short distance, there being an appreciable difference in strike between the beds of the two horizons, which could only have been the result of crustal movements.

Fauna.—The following is a list of species obtained from the basal beds of the Tejon of this section, University of California locality 3311:

Cardium brewerii Gabb
Corbicula, n. sp.?
Glycimeris sagitata Gabb
Marcia? n. sp.
Tellina, sp.
Amauropsis alveata Conrad
Crepidula pilium (Gabb)
Ficopsis remondii Gabb
Natica hornii Gabb
Pseudoperissolax blakei (Conrad)
Turritella uvasana Conrad
Turris (*Surculites*) *sinuata* Gabb
Turris (*Surcula*) *io* Gabb
Whitneya ficus Gabb

Though this fauna is a small one, the writer feels confident in his correlation of these beds with those of the typical Tejon, because: (1) of the presence of an angular unconformity between the beds containing these species and those containing a typical Meganos fauna; (2) because it is believed that a number of the species listed above are characteristic of the Tejon. All are very common in the fauna obtained from the type section of the Tejon, and only four of the species have been found in beds of Meganos age: *Amauropsis alveata* Conrad, *Ficopsis remondii* Gabb, *Natica hornii* Gabb, and *Pseudoperissolax blakei* (Conrad).

The fauna obtained from the Meganos of this general section is one of the best preserved and largest from any known section

belonging to that epoch of deposition. A very large percentage of the species are common to the Meganos of the Goalinga section, as well as to that of the Mount Diablo region.[1]

Correlation.—It was from these Eocene beds in Ventura County that convincing evidence was first obtained that the Meganos belongs to the same horizon as that of the Eocene of Marysville Buttes and Table Mountain near Oroville, California, the beds of which localities contain the fauna of the Siphonalia sutterensis zone. The large number of highly ornamented species common to the Meganos of the Ventura County region and to the Eocene of these other localities seems to show conclusively that we are dealing with beds that are nearly, if not exactly, contemporaneous.

One of the localities, from which the writer has obtained the best-preserved Meganos fauna in the Ventura County area, is along Aliso Canyon about four miles northeast of the east end of Simi Valley. Here were found a number of the species which have been regarded as characteristic of the Siphonalia sutterensis zone.[2] The following quotation is taken from the published abstract of one of Dickerson's papers in which he refers to this section:

> A year ago Mr. Reginald Stoner discovered a locality in the Santa Susana Mountains, on Aliso Canyon of Devil Creek, just beneath the Miocene strata. The fossils from this locality represent a lower phase of the Siphonalia sutterensis zone and the fauna is essentially the same as the Siphonalia sutterensis zone of the Roseburg Quadrangle, on Little River near the confluence with the Umpqua.
>
> In the Simi Hills, a few miles away from the locality discovered by Mr. Stoner, the Rimella simplex zone of the middle Tejon stage occurs; the general absence of this zone through most of the Coast Range region is probably due to extensive erosion during the interval between upper Eocene and Oligocene time.

Dickerson, at the time the above-mentioned paper was written, supposed that these beds containing the fauna which he recognized

[1] For the list of the described species from the Meganos of the area under discussion the reader is referred to the list on pages 158–59.

[2] R. E. Dickerson, "Occurrence of the Siphonalia Sutterensis Zone, the Uppermost Tejon Horizon in the Outer Coast Ranges of California," *Bull. Geol. Soc. America*, Vol. XXIX (1917), p. 163.

as that of his Siphonalia sutterensis zone were at the top of the Eocene in this general section, and used this as corroborative evidence in support of his belief that this zone belongs to the uppermost Eocene horizon known on the West Coast. At that particular locality these beds are in unconformable contact with beds of Lower Miocene age. Further stratigraphic work by Kew, however, has shown that to the west other beds come in between these Eocene beds of Aliso Canyon and the Lower Miocene, and not more than four miles from that locality nearly 3,500 feet of other strata are found between. These include beds of true Tejon age, together with a considerable thickness of land-laid beds which have generally been called the Sespe formation. This is the section already referred to, in which there is a marked unconformity between the Meganos and the Tejon. Thus mapping and faunal work in this region show conclusively that the Eocene beds of Aliso Canyon, correctly considered by Dickerson as representing his Siphonalia sutterensis zone, lie unconformably below beds which contain a typical Tejon fauna.

FAUNA OF THE MEGANOS OF CALIFORNIA

The following is a list of the described species from the different Eocene localities in California which are now believed to be of Meganos age. The list is as complete as can be made at the present time. The writer takes entire responsibility of the specific determinations. The fauna, as listed here, represents only a comparatively small part of the known fauna, since a very large proportion of the known Meganos species has not yet been described. When this fauna is more thoroughly worked up, the evidence for the correlation of the different sections here described will appear more conclusive.

The general localities from which the species listed on pages 158–59 have been obtained are indicated in the columns on the side, as follows: M., Marysville; T.M., Table Mountain; Mt.D., Mount Diablo; Coal., Coalinga; Ca., Camulos and Calabasas Quadrangles; T.T., Type Tejon.

TABLE I

	M.	T.M.	Mt.D.	Coal.	Ca.	T.T.
Anthozoa:						
Flabellum (?) merriami Nomland				×		
Stephanophyllia californica Nomland	×		×			
Trochocyathus imperialis Nomland			×	×		
Trochocyathus perrini Dickerson	×		×	×		
Thamnasteria sinuata Nomland			×			
Turbinolia dickersoni Nomland			×	×		
Turbinolia pusillanima Nomland			×	×		
Echinodermata:						
Schizaster diabloensis Kew	×		×			
Pelecypoda:						
Acila gabbiana Dickerson	×	×	×	×		×?
Arca clarki Dickerson			×			
Arca hornii Gabb, n. var.						
Cardium brewerii Gabb, n. subsp.	×		×	×	×	
Cardium marysvillensis Dickerson	×	×	×	×	×	
Corbula diletata Waring						
Crassatellites lillisi Dickerson				×		
Cucullaea morani Waring					×	
Diplodonta cretacea (Gabb)						
Glycimeris fresnoensis Dickerson				×		
Glycimeris marysvillensis Dickerson	×					
Glycimeris major Stanton, n. var.			×			
Isocardium tejonensis Waring	×		×	×	×	
Leda fresnoensis Dickerson				×		
Leda gabbi Conrad			×	×		×
Marcia (?) conradi Dickerson				×		
Modiolus ornatus Gabb	×	×	×	×	×	×
Nucula cooperi Dickerson	×					
Phacordes gyrata Gabb						
Spisula tejonensis Packard	×	×	×		×	
Spisula merriami?			×			
Tellina sutterensis Dickerson	×					
Tellina longa Gabb						
Tellina rémondii Gabb						
Tivela weaveri Dickerson					×	
Venericardia planicosta merriami Dickerson	×?	×?	×?			
Gastropoda:						
Acmaea ruckmani Dickerson		×				
Amauropsis alveata (Conrad)	×		×	×	×	×
Ancilla (Oliverata) californica Cooper	×	×	×		×	
Bittium featherensis Dickerson		×				
Bittium longissimum Dickerson	×					
Calliostoma arnoldi Dickerson	×					
Calyptrae excentrica (Gabb)	×	×	×	×	×	×
Cancellaria irelaniana (Cooper)	×	×				
Cancellaria stantoni Dickerson	×	×	×	×	×	×
Caricella stormsiana Dickerson	×					
Cerithiopsis orovillensis Dickerson		×				
Chrysodomus? martini (Dickerson) = *Phos martini* Dickerson	×	×	×			
Clavilithes tabulata Dickerson	×				×	
Cordiera gracillima Cooper	×	×				
Exilia perkinsiana Cooper	×		×			

TABLE I—*Continued*

	M.	T.M.	Mt.D.	Coal.	Ca.	T.T.
Gostropoda (*continued*):						
Ficopsis remondii Gabb, n. var.	×	×	×	×	×	×
Fusinus lineatus Dickerson	×					
Fusinus merriami Dickerson	×					
Galeodea sutterensis Dickerson	×	×	×		×	
Lyria andersoni Waring				×	×	
Metula harrisi Dickerson				×		
Mitra simplicissima Cooper	×				×	×
Molopophorus striatus Gabb			×			×
Monodonta wattsi Dickerson	×	×				
Murex nashi Dickerson	×					
Natica gesteri Dickerson			×	×		
Natica hornii Gabb						
Natica subobesa (Cooper)			×			
Natica hannibali Dickerson				×	×	
Natica nuciformis Gabb			×			×
Nyctilochus thunani Dickerson	×					
Olivella marysvillensis (Dickerson)	×					
Pseudoliva dilleri Dickerson					×	
Pseudoperissolax blakei (Conrad), n. subsp.	×		×	×	×	×
Seraphs erratica (Cooper)	×				×	
Siphonalia sutterensis Dickerson	×	×	×			
Solarium Weaveri (Dickerson)	×					
Solarium ulreyana Dickerson	×					
Spiroglyphus (*?*) *tejonensis* Arnold			×	×		
Strepsidura howardi Dickerson			×			
Terebra wattsiana Cooper	×					
Turris (*Pleurotoma*) *cooperi* Dickerson	×					
Turris (*Pleurotoma*) *monolifera* Cooper	×	×	×	×	×	
Turris (*Pleurotoma*) *ulreyana* Cooper	×	×				
Turris (*Surcula*) *clarki* Dickerson	×	×			×	
Turris (*Surcula*) *crenatospira* Cooper	×			×	×	
Turris (*Surcula*) *davidsiana* (Cooper)	×					
Turris (*Surcula*) *holwayi* Dickerson	×					
Turris fresnoensis Arnold				×		
Turris guibersoni Arnold				×		
Turris inconstans Cooper	×	×				
Turris suturalis (Cooper)	×					
Turritella andersoni Dickerson			×	×	×	
Turritella merriami Dickerson	×	×	×			
Voluta lawsoni Dickerson	×					

CORRELATION

CORRELATION OF MEGANOS SECTIONS IN COAST RANGES

The correlation of that portion of the different Eocene sections of the Coast ranges which has been referred to as the Meganos is based on both stratigraphic and faunal evidence. The stratigraphic evidence in itself, without the faunal, would

not be sufficient as it is impossible to trace the beds by mapping from any one of these general localities to another.

The stratigraphic evidence shows that in all the localities which have been examined, the Mount Diablo, Coalinga, and the Simi Hills regions, an unconformity exists between beds containing a typical Tejon fauna and others containing a fauna which is very different from that of the typical Upper Eocene, and also very different from that of the Martinez (Lower Eocene). As has been pointed out these general unconformities are not the result of local crustal movements, and surely cannot be classed as being "at most secondary order, i.e., such as might separate two formations within a group."[1] The beds below the upper unconformity are not Martinez in age, as shown by the fact that in the Mount Diablo region the Meganos beds rest unconformably on the Martinez. It is not possible at this time to present all the faunal evidence for correlating the different sections of the Meganos of the Coast ranges, as a large percentage of the species from this horizon are new and have not been described. The following discussion is based on described species only.

The best faunal evidence for correlating the Meganos of the Mount Diablo region with that of the Coalinga region is that presented by the corals. Three described species of corals are common to these two general sections; these are *Turbinolia pusillanima* Nomland, *Turbinolia dickersoni* Nomland, and *Trochocyathus imperialis* Nomland.[2] It has already been pointed out that Dickerson correlated the beds in the Coalinga region, which are here referred to the Meganos epoch of deposition, with those of his Turbinolia zone as recognized in the Eocene section

[1] R. E. Dickerson, "Stratigraphy and Fauna of the Tejon Eocene of California," *Univ. Cal. Pub. Bull. Dept. Geol.*, Vol. IX (1916), No. 17, p. 429.

[2] J. O. Nomland, "Corals from the Cretaceous and Tertiary of California and Oregon," *Univ. Cal. Pub. Bull. Dept. Geol.*, Vol. IX (1916), No. 5, pp. 59–76, Pls. 3–6.

Dr. Nomland listed *Turbinolia dickersoni* as being present in the Tejon of the Coalinga region; the type, however, came from the Meganos of this same section. Later examinations by Nomland of the specimens from the Tejon of this region, determined by him as *T. dickersoni*, show that this determination was a wrong one and that the form from this horizon is apparently a new species.—R. E. Dickerson, *Univ. Cal. Pub. Bull. Dept. Geol.*, Vol. IX (1916), No. 17, pp. 427–28.

Science & Industry
Department

southeast of Mount Diablo. This correlation apparently was based primarily on the corals. Dickerson believed that the beds of his Turbinolia zone represented a horizon lower than that of the type section of the Tejon. Thus, as regards the stratigraphic position of his Turbinolia zone with the true Tejon, he and the writer are in agreement. Besides the corals, there is a considerable number of highly ornamental molluscan species common to the Meganos of the Mount Diablo and Coalinga regions. A very large proportion of these are new species belonging to such genera as *Meretrix*, *Rimella*, *Turris*, *Ficopsis*, *Galeodea*, *Turritella*, etc. One of the described gastropod species, found in all three of the Meganos sections under discussion, is *Turritella andersoni*. This species appears to be a marker of the Meganos horizon.

The evidence for the correlation of the Meganos of the Coalinga region with that of the Camulos Quadrangle in Ventura County is even more conclusive. The faunas of the Meganos of these two localities have a very large proportion of their species in common, while in the more southern locality, Camulos Quadrangle, a number of species are found which are common to the Meganos of the Mount Diablo region, but which have not been found in the Coalinga region; among these are *Ancilla* (*Oliverata*) *californica* Cooper, *Galeodea sutterensis* Dickerson, and *Turritella merriami* Dickerson, none of which, as far as the writer is aware, have been found in the beds of typical Tejon.

CORRELATION OF THE MEGANOS WITH THE SIPHONALIA SUTTERENSIS ZONE OF THE IONE FORMATION

As already stated, it is my conclusion that the Meganos Group, originally described from the vicinity of Mount Diablo, belongs to the same general epoch of deposition as the beds of the Siphonalia sutterensis zone described by Dickerson[1] and which he considered the uppermost Eocene of the West Coast, and a part of the Ione formation described by Turner from the Jackson Quadrangle.

[1] R. E. Dickerson, "Note on the Faunal Zones of the Tejon Group," *Univ. Cal. Pub. Bull. Dept. Geol.*, Vol. VIII (1914), No. 2, pp. 17–25; "Stratigraphy and Fauna of the Tejon Eocene of California," *Univ. Cal. Pub. Bull. Dept. Geol.*, Vol. IX (1916), No. 17, pp. 363–524, Pls. 36–46.

What may be considered as the type section of the Siphonalia sutterensis zone is found at Table Mountain near Oroville, California. Dickerson[1] also referred the Eocene of the Marysville Buttes to this horizon, and later the fauna of the Umpqua formation of the Roseburg Quadrangle was included in the same horizon.[2] He recognized the distinctiveness of the Siphonalia sutterensis fauna from that of the type Tejon. The absence of many of the highly ornamented molluscan species, so common in the typical Tejon, and the presence of an equally large number of species in the former fauna not found in the latter, appear to be the principal reasons for his belief that the two faunas were not contemporaneous. Dickerson attempted to establish the stratigraphic sequence of his upper faunal zone in relation to that of the typical Tejon indirectly, not having the two faunas in the same section. His idea that the Siphonalia sutterensis fauna is younger than that of the typical Tejon appears to have been founded principally upon what he considered evidence for different stages of evolution of certain pelcypods, such as *Venericardia planicosta merriami* Dickerson and *Cardium marysvillensis* Dickerson. He believed that the variety *merriami* was derived from the variety *hornii*. Later stratigraphic work has shown that these species occur in a sequence the reverse of that which Dickerson originally supposed, the *Venericardia planicosta merriami* coming in beds older than those containing the variety *hornii*. The same is true of the other species, which were derived from typical Tejon species.

Another line of evidence which was presented as a basis for believing that the fauna of the Siphonalia sutterensis zone is closely related to that of the typical Tejon and therefore should be classed as Tejon, is the presence of a large percentage of species in the former fauna which, according to his determination, are also present in the typical Tejon. The writer has had access to all the collections which Dickerson had when he came to the foregoing conclusions. Their study has shown that there is a

[1] *Op. cit.*, pp. 403–6.

[2] R. E. Dickerson, "The Fauna of the Siphonalia Sutterensis Zone in the Roseburg Quadrangle, Oregon," *Proc. Cal. Acad. Sci.*, Vol. IV (1914), pp. 113–28, Pls. 11–12.

much smaller percentage of species common to the Siphonalia sutterensis zone and the typical Tejon than was supposed. As might be expected, there are a few species common to both faunas, but taken as a whole they are distinct. This will be still more evident when the entire fauna of the Meganos is described.

While the number of species common to the Eocene of the Marysville Buttes and Table Mountain, and to any one section of the Meganos of the Coast ranges mentioned in this paper (species not found in the typical Tejon), is not very large, yet they are forms such as would not be expected to have a very long range. A number of species from the Siphonalia sutterensis zone have been found in the Meganos of the Ventura County section, which have not been found in the Meganos of the Mount Diablo region, and vice versa. Taken as a whole, as indicated in the list, pages 158–59, there is a fairly large number of distinctive species common to the general Meganos of the Coast ranges and the beds of the Siphonalia sutterensis zone found in the Marysville Buttes and in the vicinity of Oroville. Among these are several corals together with a fairly large number of highly ornamented gastropoda and pelecypoda, the type species which are generally regarded as good horizon markers.

GENERAL CORRELATION

The consensus of opinion of those who are familiar with the Tejon fauna of California has been that it represents about the same stage of deposition as the Claiborne of the Gulf province, which in turn is correlated with the Lutetean subdivision of the Eocene of Europe. T. A. Conrad[1] as early as 1855 reported certain described Eocene species he had found in a bowlder obtained from near Fort Tejon, California, sent to him by W. P. Blake.

Later G. D. Harris in his paper entitled "Correlation of Tejon Deposits with Eocene Stages of Gulf Slope"[2] correlated the Tejon with the lower Claiborne on the basis of the identity of highly

[1] T. A. Conrad, "Paleontology," *Pac. R.R. Rept. App. to Preliminary Geol. Rept. of W. P. Blake* (1855), pp. 5–20.

[2] G. D. Harris, *Science*, Vol. XXII (Aug. 12, 1893), p. 97.

ornamented species common to the two, and also because of their generic assemblage.

Dickerson's[1] conclusion was the same as that of Harris. He listed a much larger number of identical or nearly identical species common to the Claiborne and the Tejon.

The nonconformity of the Meganos beds below the Tejon, together with the fact that the faunas of the two groups are very different, would seem to show that the former belong to a horizon lower than that of the lower Claiborne. That it does not represent the lowest Eocene is shown by the fact that the beds of the Martinez Group, which contains a fauna very distinct from that of the Meganos, lie stratigraphically and unconformably below those of the Meganos.

Dickerson's[2] conclusion after studying the fauna of the Martinez was that it is "in part the correlative of the Midway of the Gulf States and in part represents a division of time earlier than the Midway."

From our present knowledge of the Meganos fauna, its relationship appears to be closer to that of the Tejon than to that of the Martinez. If this be true, it would seem improbable that the Meganos is the equivalent of any part of the typical Midway stage. It more probably corresponds to the Wilcox. There is some direct evidence which appears to favor this assumption. This is the presence of species in the Meganos identical or nearly identical with certain well-known Middle Eocene species. For example *Turritella merriami* Dickerson with its numerous variations appears to be specifically close to *Turritella humerosa* Conrad, which is common in the Middle Eocene Wilcox of the Gulf province. One of the new species of turritella associated with *Turritella merriami* in the Mount Diablo region appears to be identical in at least one of its variations with the species listed by Harris[3] as *T. humerosa var.*

[1] R. E. Dickerson, "Stratigraphy and Fauna of the Tejon Eocene of California," *Univ. Cal. Pub. Bull. Dept. Geol.*, Vol. IX (1919), No. 17, p. 476.

[2] R. E. Dickerson, "Fauna of the Martinez Eocene of California," *Univ. Cal. Pub. Dept. Geol.*, Vol. VIII (1914), No. 6, p. 120–21.

[3] G. D. Harris, "The Midway Stage," *Bull. Amer. Paleontology*, No. 1, Pl. 11, Fig. 12 (1896).

A number of the undescribed species from the Meganos of different localities appear to be closely related to Wilcox species, if not identical with them. The correlation of the Meganos Group of California with the Wilcox of the east is only tentatively proposed. It is very possible that when the faunas of the Meganos and the Tejon are better known our ideas as to the relative position of the different Eocene horizons on the West Coast will be considerably revised.

SUMMARY OF CONCLUSIONS

The Meganos Group, the newly recognized division in the Eocene of California, has a wide distribution throughout the Coast ranges of the state. These beds represent an epoch of deposition distinct from both the Martinez below and the Tejon above. At the end of Martinez times there were orogenic movements which caused the sea to be withdrawn from what is now the Coast range province. When the sea again came, during the Meganos epoch, into this general region, its area was considerably different from that of the previous epoch. Following the deposition of the Meganos deposits, crustal movements again caused the withdrawal of the sea from the Coast range region. These movements were general throughout the Coast ranges, and over wide areas the Meganos beds were folded, the deposits of the next epoch of deposition, the Tejon, being laid across the upturned and eroded edges of these folded beds.

The Meganos of the Coast ranges belongs to the same epoch of deposition as the beds of the Siphonalia sutterensis zone, described and referred to as a part of the Ione formation by Dickerson. Previously the Siphonalia sutterensis beds had been considered to represent the uppermost Eocene of the West Coast.

A fairly large well-preserved fauna has been obtained from the Meganos horizon. This is very distinct from that of the Martinez (Lower Eocene). A few of the Meganos species are found in the Tejon. The fauna appears to be more closely related to the Tejon than to the Martinez, and is correlated provisionally with the Wilcox horizon of the Gulf and Atlantic Coast provinces.

VULCANISM AND MOUNTAIN-MAKING: A SUPPLEMENTARY NOTE

ROLLIN T. CHAMBERLIN
University of Chicago

In a recent paper on "The Building of the Colorado Rockies,"[1] the writer compared and contrasted the Rocky Mountains of Colorado, an example of a thick-shelled range, with the Pennsylvania Appalachians, which belong to the thin-shelled type. One of the striking differences developed was that the building of the more deeply rooted Colorado mountains was accompanied by the extrusion of much lava, while the shallower Appalachians were formed with the extrusion of but little lava. A further comparison was made between different portions of the Rocky Mountain chain itself. In Colorado, where the deformed zone extended deep below the surface and the vertical element in the deformation was distinctly large, lava flows appeared in abundance; while in the Canadian Rockies, where the deformed zone was much shallower and suffered intense horizontal thrust, but very little volcanic activity occurred.

The study was really concerned with only these ranges, but some of the ideas developed were extended, as tentative suggestions, to other mountain systems. The Alps, the Scandinavian chain, the Scottish Highlands, and the Serra do Espinhaço of Brazil were cited as probably belonging to the thin-shelled type because of their sharp folding, extensive thrust faulting, and great crustal shortening, and it was stated that "only moderate igneous activity" was associated with their development.[2] As representatives of the

[1] *Jour. Geol.*, Vol. XXVII (1919), pp. 248–51.

[2] This refers only to the strongly deformed portions of these ranges, since any igneous manifestations outside of these belts would also be outside the thin-shelled tracts, even though they be more or less related genetically to the mountain-making stresses. In the case of the Alps, the statement refers of course to the intense Tertiary diastrophism. Whatever relation the granites in the axial portions of the Alpine ranges may have had to the Hercynian and earlier orogenic movements is not here considered.

thicker-shell type of mountains in which vertical movements are more pronounced and horizontal thrusting and shortening less conspicuous, the Tertiary Cascades of the Pacific Coast, the Western Andes, and the Abyssinian Mountains were cited. In contrast with the preceding, the growth of these ranges was marked by the extravasation of vast floods of lava.

In this treatment of the subject it was not explicitly stated that extrusive vulcanism alone was considered, although the text would seem to the writer to convey that idea clearly enough. In view of the fact that intrusions did not enter vitally into the Appalachian section of Pennsylvania or that of the Colorado Rockies,[1] this phase of vulcanism had no place in those studies, and so the topic of intrusions was not introduced into the comparison of thin-shelled and thick-shelled ranges in general. But there are, however, certain cases in which plutonic rocks appear in ranges of the thin-shelled type in such a way as to suggest that intrusions on a large scale may be a common habit of this type. It is because of the feeling that the absence of any statement covering the intrusive phase of vulcanism might convey erroneous ideas, and perhaps lead to more or less justified criticism, that the present note is added.

Many folded mountain ranges of both thin-shelled and thick-shelled types are characterized by cores of crystalline rock, in considerable part of igneous origin. In many of these the crystalline rock clearly belongs to an old terrane arched up in the folding process and exposed by erosion; but in many other cases the intrusive relations of the igneous rock lead to the belief that it was intruded into the axis of the folded range in a late stage of the arching process. The wide prevalence of this phenomenon has been emphasized by Daly in the following terms:

> Granitic intrusion of the batholithic order, to observed levels, always follows periods of the more intense orogenic movement. This implies that the greatest abyssal injections of the earth's crust by magma are genetically associated with the horizontal shearing of a superficial earth-shell which is much thinner than the whole crust.[2]

[1] Except in the pre-Cambrian complex, which has nothing to do with the Rocky Mountain diastrophism.

[2] Reginald A. Daly, "Geology of the North American Cordillera at the Forty-ninth Parallel," *Geol. Surv. of Canada, Mem. 38*, Part II (1912), p. 573.

Cores of granodiorite and allied rocks having intrusive relations with the adjacent sedimentaries are very conspicuous in the sharply compressed Sierra Nevada Range, the Mesozoic Cascades, the Coast Range of British Columbia, and various members of the Cordilleran chain extending into Alaska—a group folded, according to present information, at about the close of the Jurassic. Throughout this disturbed region the Jurasside batholiths are a dominant feature.

In some of these cases, at least, the intrusions seem to follow in consequence of the folding, and to appear beneath the most strongly arched portions of the ranges, presumably in consequence of reduced pressure. That the arching process tends to relieve the pressure beneath and hence favors liquefaction and the penetration of magmas, is a principle long recognized and variously utilized in explaining vulcanism.[1] But whether the arching and partial relief of pressure be a major or a minor factor in the actual liquefaction of the magma, the shearing movements involved in this type of deformation might well facilitate the transfer of magma, and would favor its insinuation near the surface, either as irregular batholithic bodies, or perhaps more likely as large lenticular or pancake-shaped intrusive masses whose thicknesses are much less than their horizontal extent. The general laccolithic shape, using the term in its broadest sense, would seem to be the favorite form.[2] Intrusions of this sort occur in both thin-shelled and thick-shelled ranges.

THIN-SHELLED TYPE

In those thin-shelled ranges in which overthrust faulting has been a dominant feature, intrusions formed in this way should not be conspicuous in the marginal portions where the phenomena of overthrusting are best displayed and the shell was thinnest, but rather in the heart of the deformed belt, where the shell involved in

[1] W. Hopkins, "Researches in Physical Geology," *Phil. Trans.*, Part I (1842), pp. 43–55; Eduard Suess, *The Face of the Earth*, Vol. I (1904), p. 170; W. H. Hobbs, "Some Considerations Concerning the Place and Origin of Lava Maculae," *Beiträge zur Geophysik*, Vol. XII (1913), pp. 329–61.

[2] W. C. Broegger, *Eruptivgesteine des Kristianiagebietes*, II (1895), pp. 116–53; Alfred Harker, *The Natural History of Igneous Rocks* (1909), pp. 60–87.

the diastrophism went somewhat deeper and lifting was relatively more important. As a part of the Jurasside orogeny which developed the Sierra Nevada Range, powerful overthrusting occurred far to the east of these mountains.[1] But in these areas of overthrusting igneous activity contemporaneous with the diastrophism seems to have been unimportant.

The extraordinary Caledonian diastrophism affected both the British Isles and Scandinavia. In the Scottish Highlands on the western border the planes of overthrusting dip eastward under the deformed belt; in Scandinavia they dip westward likewise beneath the strongly deformed belt. Singly, each case illustrates the principle of bordering thrust faults on the outer margins of compressed mountain ranges.[2] Together, Scottish thrusts on the west and Scandinavian thrusts on the east, they constitute seemingly a wedge similar to the Appalachian wedge of Pennsylvania.[3]

The region of these extraordinary Caledonian overthrusts in the Northwest Highlands of Scotland seems to have been essentially free from igneous phenomena during the time of the vigorous deformation.[4] Such intrusions as took place at this time were located off to the southeast, especially in the Ochil and Sidlaw Hills[5] and the Cheviot district, which are near the middle of the deformed belt far from the overthrust border. During the deposition of the Lower Old Red Sandstone which followed the Caledonian disturbance, large quantities of volcanics were poured out in the central Lowlands between the base of the Highland Mountains and the Uplands of the southern counties.[6] But no undoubted vents of Lower Old Red Sandstone age have been detected

[1] C. R. Longwell, "Geology of the Muddy Mountains, Nevada, with a Section to the Grand Wash Cliffs in Western Arizona," *Am. Jour. Sci.*, Fifth Series, Vol. I (1921), pp. 39–62; E. S. Bastin, personal communication.

[2] "The Building of the Colorado Rockies," *Jour. of Geol.*, Vol. XXVIII (1910), pp. 243, 249.

[3] Rollin T. Chamberlin, "The Appalachian Folds of Central Pennsylvania," *Jour. of Geol.*, Vol. XVIII (1910), pp. 228–51.

[4] "The Geological Structure of the Northwest Highlands of Scotland," *Mem. Geol. Surv. of Great Britain* (1907).

[5] Sir Archibald Geikie, *Ancient Volcanoes of Great Britain*, Vol. I (1897), pp. 277–79.

[6] *Ibid.*, pp. 271–72; 295–335.

among either the Highlands on the one hand or the Silurian Uplands on the other.[1]

In Scandinavia the deformed igneous masses resting upon the Cambro-Silurian sedimentaries in the Caledonian mountain belt have been regarded by Törnebohm as portions of the Archean brought from the west by the overthrusting process.[2] If so, contemporaneous intrusions played little part in the overthrust sheets. According to Holtedahl, however, the gneisses are to be regarded as highly pressed younger intrusive masses which, during the deformation, broke forth and moved under enormous pressure from the central belt outward.[3] If in truth these be intrusions related to the Caledonian diastrophism, they are in any case more characteristic of the central belt than of the outer borders.

Among the intensely deformed Cenozoic Alps intrusions of Tertiary age are practically wanting in the central and northern ranges which together make up the region of the *nappes de charriage*, or great overthrust sheets. But in the root region of the Lepontine sheet and the Dinaric zone on the south side of the Alps, from which the overthrust masses are thought to have come, the last phase of strong mountain-building was characterized at various points by intrusions of a granitic nature.[4] Steinmann has already emphasized this contrast between the region of the roots and the region of the sheets.

In addition, it is of course to be noted that quite outside of the true mountainous belt, particularly opposite the inner curves of the arcuate chain (in Hungary, Italy, etc.), volcanic phenomena attained considerable prominence.[5] But the more or less contemporaneous extra-montane vulcanism, though related to the mountain-building stresses, is not a part of this discussion.

[1] Sir Archibald Geikie, *Ancient Volcanoes of Great Britain*, Vol. I (1897), p. 272.

[2] A. E. Törnebohm, "Grunddragen af det Centrala Skandinaviens Berbyggnad," *Kongl. Svenska Vet.-Akad. Handl.*, Vol. XXVIII (Stockholm, 1896), pp. 1–210.

[3] Olaf Holtedahl, "Paleogeography and Diastrophism in the Atlantic-Arctic Region during Paleozoic Time," *Am. Jour. Sci.*, Vol. XLIX (1920), pp. 1–25.

[4] G. Steinmann, "Die Bedeutung der jüngeren Granite in den Alpen," *Hauptversammlung der geol. Vereinigung*, Frankfort (1913), pp. 1–4.

[5] Marcel Bertrand, "Sur la distribution géographique des roches éruptives en Europe," *Bull. soc. géol. de France*, 3e sér., Vol. XVI (1887–88), pp. 573–617; Alfred Harker, *op. cit.*, pp. 20–22, 42.

The last thin-shelled range listed in the paper on the Colorado Rockies was the Serra do Espinhaço of Brazil. In the thrust-faulted portion of this ancient system very little igneous activity of any sort has occurred.[1] Eastward for 170 miles toward the Atlantic Coast, in which strip the heart of this mountain system presumably lay, there remains today only what has been called the Archean Complex. This region is characterized by many massive intrusions. Some of these may possibly have been injected at the time of the Serra do Espinhaço orogeny, though there is no evidence as yet bearing on this question.

Similarly in the Canadian Rockies very little igneous activity occurred in the overthrust region of Alberta; but farther west some of the massive intrusions in British Columbia may prove to have been related to this thrusting.

The outer marginal portions of ranges of this type, both folded and faulted, are particularly superficial. In the great overthrusts but very shallow flakes have been moved. The very low inclination of the fault planes does not carry them to great depths. Beneath the planes of overthrusting, the underlying strata, if of incompetent material, are found to be contorted in many places, but this folding rapidly dies out away from the thrust planes. Such shallow deformation does not greatly facilitate the movement of magmas. But back in the heart of the deformed belt the disturbance goes much deeper, and uplifting with relief of pressure beneath is more pronounced. Here, as the above-mentioned illustrations seem to show, intrusions tend to develop.

THICK-SHELLED TYPE

As pointed out, the thick-shelled mountains have been characterized by open, gentle folding, moderate crustal shortening affecting a deeper zone, by strong uplifting, and the extravasation of much lava.[2] Vertical diastrophism seems to dominate over horizontal. Normal faulting is an important accompaniment, occurring either incidentally as a part of the uplifting process or as a result of subsequent relaxational movements of the raised plateau-like area. Iddings has given an excellent

[1] E. C. Harder and R. T. Chamberlin, "The Geology of Central Minas Geraes, Brazil," *Jour. Geol.*, Vol. XXIII (1915), pp. 341–78.

[2] *Jour. Geol.*, Vol. XXVII (1919), p. 251.

exposition of the part block faulting has played in the extravasation of lava.[1] According to his belief, block faulting under tensile stress offers the principal outlets for the escape of lava. To quote: "The deepest fractures starting from the zone of potential magma should permit its eruption and intrusion between blocks that tend to part from one another by reason of the tensile stress." The wide prevalence of normal faulting in mountains of the thick-shelled type should therefore be an important factor in the rise of magmas. The steep inclination of normal fault planes carries these fractures to greater depths than the more gently inclined thrust faults. At the same time normal fault planes because of the governing tensile stress, at least locally, become the more ready avenues of escape for the lavas. While rhyolite and other acidic lavas have appeared in vast quantities in some places, andesitic and basaltic lavas appear to have been, on the whole, more abundant. This may perhaps be in part because the greater liquidity of the basic lavas makes migration along narrow fissures easier for them than for the more viscous silicic magmas.

SUMMARY

The formation of thick-shelled mountains is characterized in general by much volcanic activity. There may also be important intrusives bearing a close relation to the mountain-making stresses. The growth of thin-shelled mountains, on the other hand, is accompanied by very little volcanic activity, at least within the truly mountainous belt. Little igneous activity of any sort is manifested in the marginal and most strongly overthrust portions of thin-shelled ranges; but in the heart of the deformed belts, where there has been more uplifting and the affected zone goes deeper, granitic and other intrusions are a common and probably characteristic feature. It is of course also to be recognized that a region which, in an earlier age, has undergone deformation of the thin-shelled type may, in a later age, after long continued denudation, participate in orogenic movements of the thick-shelled type and so become the scene of volcanic activity on a large scale.

[1] J. P. Iddings, *The Problem of Vulcanism* ("Silliman Memorial Lectures"), Yale University Press (1914), pp. 79–81, 183–84.

SUMMARIES OF PRE-CAMBRIAN LITERATURE OF NORTH AMERICA

EDWARD STEIDTMANN
University of Wisconsin

VI. THE CORDILLERA OF THE UNITED STATES

The most notable advances in the study of the pre-Cambrian of the Cordillera are the finding of pre-Cambrian sediments unconformably below the Lower Cambrian of the southern Sierra Nevada of California by Knopf and Kirk; additions to our knowledge of the extent and composition of the belt series; and the epoch-making investigations of the life-record of the Beltian by Walcott.

Bastin and Hill[1] report that the principal rocks underlying Gilpin County, Colorado, and adjacent parts of Clear Creek and Boulder counties are of pre-Cambrian age. The Idaho Springs formation, a quartz biotite schist of sedimentary origin, is really the most important. Sedimentary origin is inferred from the highly aluminous composition of certain phases, apparent bedding, highly quartzose and certain apparently conglomeratic phases, lime silicate phases probably representing metamorphosed limestone, and the lack of evidence of intrusive relations.

Other pre-Cambrian rocks of the area include stocks of granite gneiss, quartz diorite, and hornblendite, and the younger Silver Plume granite. Granite pegmatites of various ages are abundant.

Blackwelder and Crooks[2] state that the Medicine Bow range, west of Laramie, Wyoming, contains one of the most varied sections in the western United States. They include the basal schist gneiss complex above which are more than 25,000 feet of slightly

[1] E. S. Bastin and James M. Hill, "Economic Geology of Gilpin County and Adjacent Parts of Clear Creek and Boulder Counties, Colorado," *U.S. Geol. Surv., Prof. Paper 94* (1917), 379 pp., 23 pls., 79 figs.

[2] E. Blackwelder and H. F. Crooks, "Pre-Cambrian Rocks in the Medicine Bow Mountains of Wyoming," *Geol. Soc. Am. Bull.*, Vol. XXIX (1918), pp. 97–98.

metamorphosed sediments consisting of quartzites, slates, dolomites, lava flows, pyroclastics, and tillites. Detailed studies have been made.

Butler and Loughlin[1] report that the pre-Cambrian rocks of the Cottonwood–American Fork mining region of Utah, southwest of Park City, consists mainly of shallow-water deposits of quartzites, schists, and slates about 11,000 feet thick. They dip steeply to the north. At the top of the section is a conglomeratic layer resembling tillite.

The St. Joe–Clearwater[2] region of Idaho, comprising about 250 square miles, lies about 30 miles to the southeast of the Coeur d'Alene lead-mining district. The Algonkian sediments exposed in this area include mica schists and quartzites which are correlated with those of the Coeur d'Alene district. The base on which they rest is not exposed. The formation of this area which is correlated with the St. Regis of the Coeur d'Alene lacks the purple color assumed to be characteristic in the type locality. The most difficult correlation was that of the beds believed to correspond to the Newland formation, since they are many times thicker than in the Coeur d'Alene district.

The region around Mullan, Idaho, and Saltese, Montana,[3] overlaps the southeast part of the Coeur d'Alene quadrangle. The pre-Cambrian rocks exposed belong to the Algonkian belt series and include the following formations:

Striped Peak formation—Chiefly greenish gray and some purple beds of shale and sandstone with shallow water markings

Newland (Wallace) formation . . . . 5,000± feet — Blue shale of variable thickness—5,000 feet to insignificant. Blue- and white-banded argillite with some greenish beds, with some limestone beds. Chiefly green colored calcareous rocks with argillaceous beds

[1] B. S. Butler and G. F. Loughlin, "A Reconnaissance of the Cottonwood–American Fork Mining Region, Utah," *U.S. Geol. Surv. Bull. 620* (1915), pp. 165–226, 1 pl.

[2] F. C. Calkins and E. L. Jones, Jr., "Geology of the St. Joe–Clearwater Region, Idaho," *U.S. Geol. Surv. Bull. 530* (1913), pp. 75–86, 1 pl.

[3] F. C. Calkins and E. L. Jones, Jr., "Economic Geology of the Region around Mullan, Idaho, and Saltese, Montana," *U.S. Geol. Surv. Bull. 540* (1912), pp. 167–211, 1 pl. (map).

Ravalli group
- St. Regis formation, 1,000± feet—Shales and quartzites of prevailingly green and purple tints with shallow water markings
- Revelt quartzite, 1,200 feet—Thick bedded, in part sericitic, but mostly clean quartzite
- Burke formation, 2,000 feet—Fine-grained, light-colored, thin-bedded siliceous quartzites and shales

Crawford and Worcester[1] report that the pre-Cambrian rocks of the Gold Brick district of Gunnison County, Colorado, include mica, cordierite-mica, garnet, amphibole, quartz, granitic, and hornblendic schists of which some are probably altered sediments. Quartzites and pyroxenic quartzites, quartzite conglomerate, andalusite quartz rocks, and epidote rocks also occur. Certain granite and diorite intrusion are probably pre-Cambrian.

Exposures of quartzite and schist or shale[2] belonging to the Algonkian Uncompahgre formation are found in the Piedra Canyon of the San Juan region.

Darton[3] states that granite is the pre-Cambrian rock of Luna County, New Mexico.

Darton[4] reports that the pre-Cambrian rocks of the Deming quadrangle of southern New Mexico consist of granite with subordinate gneissic granite and diorite.

Duncan[5] describes the pre-Cambrian rocks of Harney Peak, South Dakota, as consisting of mica, hornblende, garnet schists intruded by granite and associated with greisen, pegmatite, and quartz veins.

The Philipsburg quadrangle[6] lies in the central western part of Montana. The Belt series is unconformably overlain by the

[1] R. D. Crawford and P. G. Worcester, "Geology and Ore Deposits of the Gold Brick District, Colorado," *Colorado Geol. Surv. Bull. 10* (1916), 116 pp., 9 pls., 4 figs.

[2] Whitman Cross and E. S. Larsen, "Contributions to the Stratigraphy of Southwestern Colorado," *U.S. Geol. Surv. Prof. Paper 90* (1914), pp. 39–50, 1 pl., 2 figs.

[3] N. H. Darton, "Geology and Underground Water of Luna County, New Mexico," *U.S. Geol. Surv. Bull. 618* (1916), 188 pp., 13 pls., 15 figs.

[4] N. H. Darton, "Description of the Deming Quadrangle, New Mexico," *U.S. Geol. Surv. Geol. Atlas, Folio No. 207* (1917), 15 pp., 5 pls. (maps and illus.), 11 figs.

[5] Gordon A. Duncan, "Contribution to the Study of the Pre-Cambrian Rocks of the Harney Peak District of South Dakota," *Trans. Am. Inst. Min. Eng.*, Vol. XLIII (1913), pp. 207–18, 3 figs.

[6] W. E. Emmons and F. C. Calkins, "Geology and Ore Deposits of the Philipsburg Quadrangle, Montana," *U.S. Geol. Sur., Prof. Paper 78* (1913), 271 pp., 17 pls.

Cambrian Flathead quartzite. This relation is expressed by angular disconformity of bedding and by a basal conglomerate. The Belt formations of this area are correlated with those of the Walcott's Belt Mountain section. The only difficulty in this correlation lies in the absence in the Philipsburg district of beds equivalent to the Greyson shale. The Beltian succession of the Philipsburg district is as follows:

Unconformity

Spokane shales—Shale and sandstone, the prevailing in upper portion, color chiefly red, some cracks, and ripple marks, 5,000 feet

Greyson shales—Apparently lacking, may be included in Newland

Newland limestone—Thin-bedded, more or less siliceous and ferruginous passing into shale, generally buff on weathered surface. Shallow water markings in upper part, 4,000 feet

Ravilli quartzite—Gray with some dark bluish and greenish shale, 2,000 feet

Prichard shales—Dark bluish interbedded with sandstone, rusty brown on weather surface, 5,000± feet

Neipart quartzite—Light colored. Base not exposed. 1,000± feet

Finlay[1] reports that the pre-Cambrian rocks of the Colorado Springs quadrangle consist chiefly of the Pikes Peak granite in which are minor inclusions of acid gneisses and schists. Two other granites and some pegmatite and syenite dikes are included in the pre-Cambrian.

Haynes[2] finds the following pre-Cambrian rocks in the vicinity of Three Forks, Montana:

Empire shale—Even-bedded green shales, interlayered with quartzite. Thickness, 800 feet, (?)

Spokane formation—Well-stratified red and green slates interlayered with mud cracked and ripple-marked sandstone. Thickness, 1,650+ feet.

From studies of the Wardner district quartzite, Hershey[3] adds the Cataldo to the base of Calkins' Belt section.

[1] G. I. Finlay, "Description of the Colorado Springs Quadrangle, Colorado," *U.S. Geol. Surv., Folio 203* (1916), 17 pp., 7 pls., 9 figs.

[2] W. P. Haynes, "The Lombard Overthrust and Related Geological Features," *Jour. Geol.*, Vol. XXIV (1916), pp. 269–90, 11 figs.

[3] O. H. Hershey, "The Belt and Pelona Series," *Am. Jour. Sci.*, 4th Ser., Vol. XXXIV (1912), pp. 263–73.

The Belt series,[1] according to Walcott, unconformably underlies the Middle Cambrian Flathead quartzite. In ascending order the members exposed are the Spokane shale, Empire shale, Helena limestone, and Marsh shale. The total thickness is 3,300 feet at Helena, of which the Helena limestone comprises 2,400 feet.

Knopf and Kirk[2] report that pre-Cambrian rocks underlie with marked erosional unconformity the Lower Cambrian of the Inyo range of southern California. The pre-Cambrian system from the top downward consists of the following:

Deep Spring formation—Local sandstone and dolomite beds, 1,600 feet
Reed dolomite—2,000 feet
? Sandstones and thin-bedded, impure dolomites, 2,000 feet (?)

Both Archean and Algonkian[3] are exposed in the Shinumo quadrangle. They are separated by a well-marked unconformity characterized by angular discordance of structures, difference in metamorphism, and intrusives.

The Archean is composed of the Vishnu schists including quartz, mica, and hornblende schists. They are cut by Archean quartz diorite and granite pegmatite intrusives.

The Algonkian section is as follows:

Unconformity
Dox sandstone—Cross-bedded, ripple-marked in part, mud-cracked argillaceous layers. 2,297 feet plus unknown thickness removed by pre-Cambrian erosion
Shinumo quartzite—Hard, compact, cross-bedded sandstone and quartzite, usually of fine and even grain. 1.564 feet
Hakatai shale—Argillaceous red shale grading upward into arenaceous red shale and sandstone. Nearly all beds contain sun cracks and ripple marks. Metamorphosed by a thick diabase sill. 580 feet

[1] Adolph Knopf, "Ore Deposits of the Helena Mining District, Montana," *U.S. Geol. Sur. Bull. 527* (1913), 143 pp., 7 pls., 4 figs.

[2] A. Knopf, "A Geologic Reconnaissance of the Inyo Range and the Eastern Slope of the Southern Sierra Nevada, California," with a section on the stratigraphy of the Inyo range, by Edwin Kirk, *U.S. Geol. Surv. Prof. Paper 110* (1918), 130 pp., 32 pls., 8 figs.

[3] L. F. Noble, "The Shinumo Quadrangle, Grand Canyon District, Arizona," *U.S. Geol. Surv. Bull. 549* (1914), 100 pp., 18 pls. (incl. map in pocket), 1 fig.

Bass limestone—White crystalline limestone alternating with beds of argillaceous and calcareous red shale containing sun cracks, cut by thick diabase sill. 335 feet

Hotauta conglomerate—Arkose conglomerate characterized by lack of sorting and transportation. Rests on an even surface of erosion. 0–6 feet

Unconformity

Detailed study of the Vishnu series is lacking, but it is thought to be equivalent to the Pinal schists of the Bisbee district.

Paige[1] reports that the pre-Cambrian rocks of the Silver City folio of southwestern New Mexico are granites with minor quartzitic and schistose masses, the whole being mapped as a unit.

Patton[2] *et al.* state that the pre-Cambrian rocks in the Alma district of Park County, Colorado, consist mostly of granitic and banded gneisses and acid schists, granites, pegmatites, and aplites.

Ransome[3] presents ten Paleozoic sections ranging from southern to northern Arizona. In each section Cambrian is unconformably above pre-Cambrian. The pre-Cambrian rocks in these sections are as follows:

District	Pre-Cambrian Rocks
Bisbee	Pinal schists (sericitic schist chiefly metamorphosed sediments cut by granite)
Tombstone	Pinal schist and gneissic quartz-mica diorite
Clifton	Pinal schist and granite
Globe and Ray quadrangles	Pinal schist and intrusive granitic rocks
Roosevelt	Granite
Southern part of the Ancha district	Granite
Northern part of the Ancha district	Granite, older pre-Cambrian schists, younger pre-Cambrian quartzite, and conglomerate

[1] Sidney Paige, "Description of the Silver City Quadrangle, New Mexico," *U.S. Geol. Surv., Atlas Folio No. 199* (1916), 19 pp., 4 pls., 17 figs.

[2] H. B. Patton, A. J. Hoskins, and M. G. Butler, "Geology and Ore Deposits of the Alma District, Park County, Colorado," *Colorado State Geol. Surv. Bull. No. 3* (1912), 284 pp., 29 pls., 6 figs.

[3] F. L. Ransome, "Some Paleozoic Sections in Arizona and Their Correlation," *U.S. Geol. Surv. Prof. Paper 98* (1916), pp. 133–66, 8 pls., 4 figs.

District	Pre-Cambrian Rocks
Head of Canyon Creek	Hornblende rock and schist
Jerome	Schist
Grand Canyon	Grand Canyon series, younger pre-Cambrian including over 4,700 feet of conglomerate, limestone, shale, quartzite, and sandstone resting unconformably on schist of older pre-Cambrian

All the pre-Cambrian rocks in the foregoing sections excepting some of the Grand Canyon and northern Ancha sections are older pre-Cambrian.

Richardson[1] finds that in the region of Castle Rock folio lying between Denver and Colorado Springs, only the youngest of the pre-Cambrian rocks of the Front Range, the Pikes Peak granite is exposed.

Richardson[2] finds that the pre-Cambrian rocks of the Van Horn quadrangle of southwestern Texas are unconformable below the Cambrian and they consist of the following:

Millicon formation—Fine red sandstone, cherty limestone, and conglomerate; in northern Carrizo Mountains

Relations concealed

Carrizo formation—Quartzite, slate, and a variety of schists; in southern Carrizo Mountains

Schultz[3] finds that the pre-Cambrian rocks of southeastern Idaho and western Wyoming include schists, granites, gneisses, and igneous rocks cut by dikes of pegmatite and diabase. Some of the schists and gneisses may be of sedimentary origin. The pre-Cambrian area lies in the central and eastern part of the Teton range.

[1] G. B. Richardson, *United States Geological Survey, Castle Rock Folio No. 198* (1915).

[2] G. B. Richardson, "Description of the Van Horn Quadrangle, Texas," *U.S. Geol. Surv. Geol. Atlas, U.S. Van Horn Folio (No. 194)* (1914), 9 pp., 5 figs., 3 maps, illustration sheet.

[3] A. R. O. Schultz, "Geologic Reconnaissance for Phosphate and Coal in Southeastern Idaho and Western Wyoming," *U.S. Geol. Surv. Bull. No. 680* (1918), pp. 84, 2 pls., 8 figs.

Smith and Packard[1] state that certain rocks possibly of pre-Cambrian age have been found in Oregon. They include a granodiorite near the head of John Day River and certain amphibolite, hornblendite, mica quartz schists, and talc schists near the California-Oregon boundary.

Smith[2] states that the pre-Cambrian of California comprises schists and gneisses of Inyo, San Bernardino, and Riverside counties. These underlie Olenellus beds. They also include the Pelona schists of San Bernardino County, the Abrams and Salmon schists of Trinity and Siskiyou counties, the South Fork Mountain schists, and certain old schists and gneisses mapped with the Sierra batholith. Similar rocks also occur in the Sierra Madre.

Somers[3] states that the pre-Cambrian rocks of the Burro Copper district of southwestern New Mexico consist of a complex of granites.

Umpleby[4] reports that in a reconnaissance survey of northwestern Custer County, Idaho, he has found highly metamorphosed schists, slates, and quartzites of Algonkian age, which probably represent a part of the Coeur d'Alene section. The sequence in Custer County was not worked out in detail.

Walcott[5] cites evidence for the unconformity of the Cambrian and pre-Cambrian at Helena, Montana. The specific facts referred to are slight angular discordance, in places an erosion surface on the pre-Cambrian formations, and fossil relationship.

Walcott[6] regards the pre-Cambrian Algonkian limestones of the Cordilleran region of North America as owing their origin chiefly

[1] W. D. Smith and E. L. Packard, "The Salient Features of the Geology of Oregon," *Jour. Geol.*, Vol. XXVII (1919), pp. 79–120.

[2] J. P. Smith, "The Geologic Formations of California with Reconnaissance Geologic Map," *Cal. State Min. Bur. Bull. No. 72* (1916), 47 pp., tables.

[3] R. E. Somers, "Geology of the Burro Mountains Copper District, New Mexico," *Am. Inst. Min. Eng. Bull. No. 101* (May, 1915), pp. 957–96, 25 figs.; *Bull. No. 108*, p. 2476.

[4] Joseph B. Umpleby, "Some Ore Deposits in Northwestern Custer County, Idaho," *U.S. Geol. Surv. Bull. 539* (1913), 100 pp., 10 pls., 4 figs.

[5] C. D. Walcott, "Relations between the Cambrian and Pre-Cambrian Formations in the Vicinity of Helena, Montana," *Smithsonian Misc. Coll.*, Vol. LXIX, No. 4 (June 24, 1916), pp. 259–301, 6 pls., 4 figs.

[6] C. D. Walcott, "Pre-Cambrian Algonkian Algal Flora," *Smithsonian Misc. Coll.*, Vol. LXIV, No. 2 (1914), pp. 77–156, pls. 4–23.

to the action of bacteria and algae. Bacterial remains have not been identified in pre-Cambrian rocks, but numerous concretionary forms have been found in the Newland limestone of the Belt series. These forms are similar to the calcareous bodies formed by modern blue-green algae in fresh-water lakes. Chains of silicified cells which resemble the cell chains of modern blue-green algae were also found. The similarities of structure between the pre-Cambrian and modern algoid forms are clearly demonstrated by a series of plates. Eight Algonkian algal forms are described by Walcott as occurring in the Newland limestone. The Greyson shale overlying the Newland limestone has numerous crustacean remains—*Beltina danai* and many annelid trails representing five species. The next overlying formation of the Belt series, the Spokane shales, is credited with one species of algae.

Walcott[1] briefly describes bacteria which he discovered in the Newland limestone, a formation of the Beltian series of Montana.

The pre-Cambrian rocks[2] of the Dillon quadrangle include the Belt series, 3,000 feet thick, which are composed of slates, thin-bedded quartzite, and schists. They are unconformably above a series of schists and gneisses interbedded with limestones 5,000 feet thick which are correlated with the Cherry Creek group.

VII. THE CORDILLERA OF CANADA

Notable advances have been made in the study of the pre-Cambrian of the southern portion of the Rocky Mountain section by Daly, Schofield, and others. The pre-Cambrian in this section consists of two units, an older complex of clastic and chemical sediments, the Priest River terrane, Shuswap series, etc., folded and metamorphosed, and intruded by granites. The stratigraphic separation of this older unit has not been fully accomplished. Unconformably overlying the basal rocks is a thick series of feebly metamorphosed clastic sediments and limestones, the Belt series, having characteristics of terrestrial sediments. They are coarsest and most fragmental in the western part of the section where they

[1] C. D. Walcott, "Discovery of Algonkian Bacteria," *Nat. Acad. Sci.* (1915), pp. 256–57, 3 figs.

[2] A. N. Winchell, "Mining Districts of the Dillon Quadrangle, Montana and Adjacent Areas," *U.S. Geol. Surv. Bull. No. 574* (1914), 191 pp., 8 pls., 16 figs.

are exposed in contact with the older rocks. Different views as to the upper limits of the Belt series have been held. Daly believed that they were conformable with the Cambrian. Schofield reports that he has found an unconformity at the base of the Middle Cambrian and places the top of the Beltian much higher than Daly.

Allan[1] states that between Banff and Golden in the valley of Bow River along the Canadian Pacific Railway the pre-Cambrian section is as follows: Base not exposed. Corral Creek formation, 1,320 feet composed of quartzites and coarse-grained sandstones with interbedded shales. Hector formation, 4,590 feet, gray, green, purple, siliceous shale with interbedded conglomerates. Remains of brachiopod-like shells in certain beds. Disconformable contact with Cambrian above.

The rocks[2] along the international boundary between the Porcupine and Yukon rivers, classified provisionally as pre-Cambrian, lie on the north side of the Yukon and are peripheral to a larger area of these rocks south of the river. They comprise amphibolites, quartzite schists, mica schists, and occasional limestone beds.

According to Daly,[3] the succession of the Rocky Mountains along the forty-ninth parallel from the Clark range on the western margin of the Great Plains to the Selkirk on the one hundred and seventeenth meridian include the pre-Beltian Priest River terrane; the Beltian; Lower, Middle, and Upper Cambrian; and on the western border of the area, later conformable Paleozoic rocks. The only regional unconformity lies between the Beltian and pre-Beltian.

The pre-Beltian Priest River terrane consists of an undetermined thickness of dynamically metamorphosed sediments, notably mica schists, phyllites, quartzites, chlorites, schists, and dolomites whose stratigraphic order is unknown. The thickness exposed may be about 18,000 feet. They outcrop along the eastern base

[1] John E. Allan, *International Geog. Congress, Twelfth Guide Book* (1913), pp. 167–201, maps 2, prints.

[2] DeLorme D. Cairnes, "The Yukon-Alaska International Boundary between Porcupine and Yukon Rivers," *Canada Geol. Surv. Mem. No. 67* (1914), 161 pp., 2 maps (in pocket), 2 figs., 16 pls.

[3] R. E. Daly, *Geology of the North American Cordillera at the Forty-ninth Parallel* (1912), 3 parts, 840 pp., 73 pls., 42 tables, 17 geologic maps.

of the Selkirk Mountain system in parallel bands striking about north 15° east.

The succession overlying the Priest River terrane is sedimentary with the exception of an extensive basal lava flow, the Purcell lava which occurs in the eastern portion. The extent of the latter makes it a good horizon marker. Geographically, this succession is classified from west to east as the Summit, Purcell, Galton, and Lewis series. The Summit series of the Selkirks is the only one whose base is exposed. It unconformably overlies the Priest River terrane. The various members of these series are correlated with reference to their position above or below the Purcell lava, their mineralogical constituents, and general lithological characteristics, special emphasis being laid upon the molar tooth structure of certain carbonate formations due to the weathering of a peculiar mixture of dolomite and limestone, the presence of a certain orthoclase feldspar with a characteristic microperthitic intergrowth, the presence or absence of red iron oxide, etc. In the Selkirks the sediments are chiefly clastic, conglomerates being important at the base. To the eastward, these grade into finer-grained clastics and carbonate. The easternmost part of the series is composed dominantly of carbonates. Red color is also more prominent in the more easterly series especially in their upper portions.

The only fossils found are the species *Beltina danai* which occur in the Altyn limestone in the lower portion of the Lewis series. This limestone and the one underlying it are classed as Beltian.

The Beltian and Cambrian beds are bent into open nearly north and south trending folds which are disturbed by normal faults, most of which trend in the same direction as the folds. The Lewis series has been pushed over the Mesozoic sediments of the Great Plains along a thrust fault dipping westward at a low angle.

In the case of the Lewis series, the Altyn dolomite and the Waterton dolomite below it are referred to the Beltian because of the presence of *Beltina danai* in the Altyn. The basis for the separation of the series into Beltian and Cambrian is not so apparent. The correlation of the beds designated as Cambrian is based chiefly on the lithological similarity of the Siyeh limestone with the

fossiliferous Castle Mountain limestone of McConnell's Castle Mountain–Bow River series on the Canadian Pacific Railway.

Daly bases his correlation of the other formations on their position with respect to the Siyeh and their lithologic resemblance to certain members of McConnell's sections. Willis placed all of the Lewis series in the Beltian since the *Beltina danai* beds of the Altyn formation are conformable with the overlying beds of the series, whereas in the Belt range the Cambrian unconformably overlies the Beltian and is separated from the *Beltina danai* bearing beds by 7,700 feet of sediments. Walcott also found a plane of unconformity at the base of the Fairview sandstone, the lowest Cambrian in the Bow River section.

Daly[1] describes the rocks along the Canadian Pacific Railway, between Golden and Kamloops, British Columbia.

Pre-Cambrian rocks dominate in this section. He classifies them into the Beltian and pre-Beltian or Shuswap. The two are separated by an unconformity. His divisions of the Shuswap or pre-Beltian follows:

	Formation	Approximate Thickness in Feet
	Unconformity with Beltian System	
Intrusive	Batholiths, laccoliths, sills, dykes, and chonoliths of granite, aplite, and pegmatite, generally metamorphosed	
Shuswap series	Adams Lake basic volcanics (with contemporaneous basic intrusives)	10,000+
	Tshinakin limestone-metargillite	3,900
	Bastion schists (phyllites, etc.)	5,000
	Sicamous limestone (representative of Dawson's "Nisconlith" series)	3,200
	Salmon Arm mica schists	1,800
	Chase quartzite	3,000
	Tonkawatla paragneiss (?)	1,500+
Base concealed		
		28,400

The existence of the individual members of this series is certain, but their relative thickness is still in doubt with the exception of the Tshinakin limestone and the Sicamous limestone.

[1] R. A. Daly, "A Geological Reconnaissance between Golden and Kamloops, B.C., along the Canadian Pacific Railway," *Canada Geol. Surv. Mem. No. 68*, 1915, 260 pp., 7 maps, 46 pls., 4 figs.

The pre-Beltian area forms a core surrounded by Beltian and other younger rocks. It is roughly lenticular in outline, its longest direction extending from northwest to southeast. It is about 400 miles in length and 100 miles in width. The quartzites in this series represent true sandstones, probably derived from a granitic area. Daly believes that the intrusions in the pre-Beltian are of a type characteristic only of the early pre-Cambrian and resemble the Laurentian granites of the Canadian Shield. Sills and *lit par lit* injections are characteristic. The metamorphism of the pre-Beltian, he believes, is due almost entirely to the weight of overlying beds and to temperature. The facts on which this conclusion is based are the parallelism of the fissility and the bedding, the almost complete absence of ordinary folds, the low dip of the beds, and the parallel fissility of the dykes with that of the adjacent beds. Metamorphism of this type, Daly believes, is typical of the pre-Cambrian only. He ascribes it to a steep temperature gradient of the earth's crust and to the abundance of mineralizers in the granitic intrusions of that time. The pre-Beltian of this area, he believes, is probably correlated with the Priest River terrane to the south, the only difference between the two being that as yet no granites have been found in the latter. Equivalent rocks also probably occur on the west shore of Coeur d'Alene Lake.

The Beltian system of the area is classified as follows:

COLUMNAR SECTION OF THE BELTIAN SYSTEM IN THE SELKIRK

		Approximate Thickness in Feet
Top, erosion surface		
Glacier Division ("Selkirk series" of Dawson)	Ross, quartzite (in part)	2,500
	Nakimu limestone	350
	Cougar formation (quartzite with metargillitic beds)	10,800
Albert Canyon Division "Nisconlith series" of Dawson	Laurie formation (metargillite, often calcareous; with subordinate interbeds of limestone and quartzite; basal bed, limestone 50 feet thick)	15,000
	Illecillewaet quartzite	1,500
	Moose metargillite	2,150
	Limestone (marble)	170
	Basal quartzite	280
		32,750
Base, unconformity with Shuswap terrane		

The source of this great thickness of sediments, Daly believes, is the older pre-Beltian terrane, the principal evidence for this being the graduation of coarser sediments to finer in going from west to east. Another fact in favor of this is that the quartzites commonly contain fragments of alkaline feldspar. The quartzites, he believes, are partly dune and loess deposits. The limestones, because of their fine grain, he ascribes to direct chemical precipitation. Most of the sediments are well bedded and consist chiefly of quartz, striated feldspar, and clayey material. Frequently, they show ripple marks and mud cracks.

The Roosville, Phillips, and Rateway[1] formations classified by Daly in his forty-ninth parallel report as Middle Cambrian are assigned by Schofield to the Beltian because the Roosville is unconformably overlain by the fossilferous Middle Cambrian Burton formation. Both the Purcell and the Galton series of Daly are placed in the pre-Cambrian.

The unconformity between the Burton and the Roosville is not shown by discordance of bedding, but by a basal hematite conglomerate of the Burton, the occurrence of other materials in the Burton which are inferred to have been derived from the Roosville, the striking difference in the metamorphism of the Burton as compared with the formations underlying it, and the occurrence of cryptozoan forms in the formations underlying the Burton.

Schofield[2] describes the Cranbrook area of southeastern British Columbia.

The area is in the southern part of the Purcell Mountains and includes about 50 square miles. The Beltian pre-Cambrian rocks underlie most of the area. Schofield's classification of these rocks follows.

[1] S. J. Schofield, "The Pre-Cambrian (Beltian) Rocks of Southeastern British Columbia, and Their Correlation," *Canada Geol. Surv. Mus. Bull. No. 2* (July 3,1914), pp. 79–91, 1 fig. (map).

[2] S. J. Schofield, "Geology of Cranbrook Map-Area, British Columbia," *Canada Geol. Surv. Mem. No. 76* (1915), 245 pp., 1 map, 33 pls., 15 figs.

Cambrian	Erosion: early Cambrian uplift
Pre-Cambrian (Beltian) Purcell series	Gateway formation: (continental deposition), sandstones, sandy argillites, some concretionary siliceous dolomite. Salt casts and ripple marks
	Purcell lava, Purcell sills: intrusion of gabbro accompanied by outpouring of basalt over land surface
	Siyeh formation: (mainly continental, some possibly marine deposition), red, purple, and green mud-cracked argillites, ripple-marked sandstones, some limestones
	Kitchener formation: (continental and possibly marine deposition), calcareous argillites, argillaceous quartzites ripple marked, mud-cracked, some limestones
	Creston formation: shallow water deposition, quartzites, argillaceous quartzites, mud cracks, and ripple marks
	Aldridge formation: argillaceous quartzites, some conglomerates

Reviews

Mineralogy. By KRAUS and HUNT. McGraw-Hill, 1920. Pp. xiv+561. $4.50.

This is in many respects an excellent text, and one that should have wide use. The matter is presented in a simple, direct style and, while abbreviated, is concise and to the point, and should be suitable for classes in first-year mineralogy. The presence of a moderate number of small photographs of distinguished mineralogists together with extremely brief histories is a feature of the book.

Ninety-four pages are devoted to crystallography, thirteen classes being described in detail. This matter is taken largely from the senior author's excellent *Essentials of Crystallography* (1906), and needs no comment here. As in the earlier work, no photographs of crystals are to be found in the part on crystallography. Instead the authors have included numerous photographs of crystal models. This makes the shapes of ideal crystals clear, but as most crystals found in nature are more or less imperfect, some photographs of crystals would have been of value. Under descriptive mineralogy there are numerous photographs of crystals.

One hundred forty-three pages are devoted to the description of 150 minerals. Although largely taken from the senior author's *Descriptive Mineralogy* (1911), the material is abbreviated and is illustrated by numerous well-selected photographs. The arrangement of the minerals is strictly chemical, the authors even going so far as to put several minerals generally grouped with the oxides into separate divisions such as aluminates, ferrites, manganites, and titanates, and, vice versa, zircon is placed with the oxides. Brucite, prehnite, vivianite, and wad are omitted. Varieties, occurrence, associations, important localities, and uses, as well as the more commonly described features of minerals, are given.

The determinative tables for 150 minerals take 169 pages. They are based on physical differences—luster, color, streak, and hardness. One column in the tables describes the mineral associations. Color seems overemphasized, since it is in general less diagnostic than streak or hardness. As an illustration of this point, ten minerals with a wide range of color were selected, and of these brown biotite, red, yellow, or

brown olivine, and colorless tourmaline could not be found under the proper divisions. These minerals, with the colors given, are, to be sure, more or less rare. The tables appear to be excellent for at least the more common varieties of minerals.

The volume also has chapters on the physical and chemical properties of minerals, the polarizing microscope, the formation and occurrence of minerals, qualitative blowpipe methods, gems and precious stones, as well as a classification of minerals according to the elements they contain, giving their uses and statistics of their production. Six pages are devoted to a glossary.

Perhaps one of the most noticeable defects of the book is its entire lack of references, whether in the form of a general bibliography or as footnotes. There are a number of typographical errors, though but few that might lead to confusion were noticed. There are some other errors, not so surely typographical, such as placing wulfenite under the wolframite group, giving tourmaline the formula $H_{20}B_2Si_4O_{21}$, and placing the origin of the minerals in igneous rocks under minerals formed from fusion (rather than from solution). The chemical distinction between the different plagioclase feldspars is poor.

In spite of these minor defects the work is excellent, well arranged, and attractively presented.

D. J. F.

Geology and Mineral Resources of the Hennepin and La Salle Quadrangles. By GILBERT H. CADY. Illinois Geological Survey, Bull. No. 37. Urbana, 1919.

The area represents one of the richest agricultural, manufacturing, and mining communities in the Middle West, including parts of La Salle, Bureau, and Putnam counties of north-central Illinois. The manufacturing wealth is dependent to no small degree upon the natural resources of the region.

General geology.—The area forms a part of the Glaciated Plains Province, the larger part of it being monotonously level, what relief there is being chiefly due to glacial drift. Stratigraphically the rocks of the region range from Cambrian through the Carboniferous, with Pleistocene glacial drift. Good detailed sections and faunal lists are given. There are several important unconformities. Though the strata are for the most part nearly horizontal, the La Salle anticline, or, as the author suggests, more properly the La Salle monocline, shows dips up to 50° locally.

Mineral resources.—The chief resources of the area include coal, limestone for the cement industry, sand and gravel, shale and clay, glass-sand, building stone, and water. Coal is of great importance, the region lying within the northern border of the eastern interior coal basin. While coal is present at several horizons in the Pennsylvanian, only the La Salle bed of the Carbondale formation is at present being mined. Workable deposits of clay and shale are confined to the Pennsylvanian and Quaternary deposits. Both are of some importance. The Lower Magnesian limestone formerly was extensively used as a source of natural cement and is still used to a small extent. One of the important industries of the region is the manufacture of Portland cement. The La Salle limestone is the chief source. The St. Peter sandstone is the chief source of building stone. Sand and gravel are abundant. While the structure is favorable, no evidence of the accumulation of oil and gas has been found other than the local subglacial pockets of gas which are in places utilized by private individuals.

A. C. McF.

The Artesian Waters of North Eastern Illinois. By CARL B. ANDERSON. Illinois State Geological Survey, Bull. No. 34. 1919.

The importance of this report lies in the partial dependence of the industries and cities of northeastern Illinois on artesian waters. Exclusive of Chicago, whose industries consume 30,000,000 gallons daily, the people of the region depend almost entirely on artesian waters. The area investigated includes thirteen counties.

The bedrock comprises Cambrian, Ordovician, Silurian and Pennsylvanian strata. It was found that while some water is obtained from all the systems named, the Potsdam sandstone is the best available source, a yield of 200 gallons per minute being common from flowing wells. For private consumption the shallower horizons are better. In general the water is hard.

The method of treatment is by counties with more detailed discussions for the different cities and villages. A large amount of useful data are compiled in the report, including water analyses, drilling costs, temperature of the water, and the position of the water table.

A. C. McF.

Geology of Petroleum. By WILLIAM HARVEY EMMONS. First Edition. McGraw-Hill Book Company, 1921.

It is gratifying to record in this book by Professor Emmons a most notable contribution to geological education and one that was imperatively needed, because of the unusual present interest in geology as applied to the occurrence of petroleum and natural gas.

While the reviewer is not entitled by experience to pass judgment on the book from the viewpoint of the advanced specialist in petroleum geology, surely from the standpoint of the general geologist interested in petroleum occurrence the volume supplies a most welcome means of acquiring familiarity with special geologic problems connected with oil occurrence, and, as stated in the preface, the book was designed to meet this need on the part of professional geologists, and especially of college students already familiar with the fundamental principles of geologic science.

The work is based on a series of lectures which for several years have been offered in courses in economic geology at the University of Minnesota. Especially noteworthy is the large number of references indicating that the author has made an exhaustive search of the literature. This feature makes the volume valuable as a source book, in addition to its primary purpose. Two hundred and fifty-four text figures, mostly line drawings, are judiciously selected.

Chapter I, the introduction, includes sections on geographic and geologic distribution. Tabulations of geologic distribution bring out the notable fact that only in the United States have important oil reserves been found in rocks of Paleozoic age. Chapter II deals with surface indications of petroleum and methods for testing rocks for the presence of oil.

Other chapters deal with the openings in rocks, the association of petroleum and salt water, reservoir rocks and covering strata, and the properties of petroleum and natural gas. Current views concerning the first stages of the formation of petroleum are covered in other chapters, as well as theories governing the accumulation of oil in pools. A very useful table is given showing the salient features of a large number of oil fields, including the age of the rocks, their kind, the nature of the cover, the structural character of the reservoirs, and the nature of the surface indications of petroleum.

A long chapter is devoted to the structural features of oil and gas pools, and chapters of lesser importance are devoted to the effects of

dynamic action on petroleum occurrence, gas pressure and oil recovery, and petroliferous provinces.

While a short chapter deals with the subject of maps and logs and explains the meaning of structural contours, there is no detailed discussion of methods of field work in petroleum geology, nor does the book touch the ground of petroleum technology already adequately covered by other works.

The general features of petroleum occurrence mentioned above occupy the first one hundred and ninety-four pages. Nearly three hundred pages are devoted to summaries of petroleum occurrence in the various fields in the United States, and about one hundred and twenty pages to foreign occurrences.

E. S. B.

PREFACE

The writer's experience in the Adirondack Mountains of New York state has led him to realize the lack of published information concerning the perthitic feldspars. The dominant feldspar of the Algoman augite syenite of the region is perthite (microperthite). This Precambrian rock is a differential phase of an important rock unit which grades from syenites, through quartz syenites, and syenite granites to true granites. In passing from the femic to the salic phases it is readily observed that the feldspar becomes more potassic and passes into what is commonly known as orthoclase, and thence into microcline. Thus the Algoman syenite-granite rocks raise two questions: What is perthite? And what is the difference between orthoclase and microcline?

The attempt to answer these and similar questions led the writer to make the investigation of which the following paper is the result.